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DEVELOPMENT AND CALIBRATION OF AN OIL SPILL BEHAVIOR
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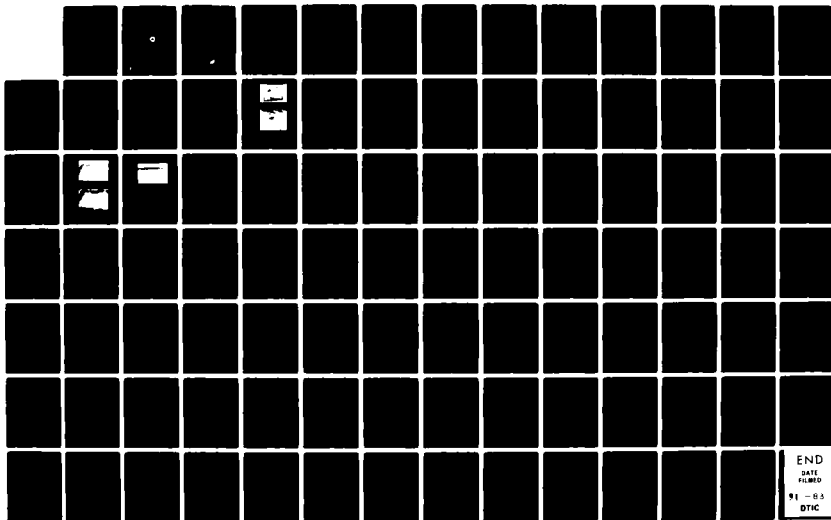
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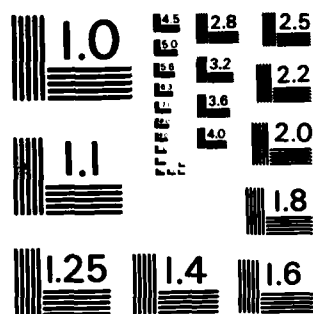
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DEVELOPMENT AND CALIBRATION OF AN OIL SPILL
BEHAVIOR MODEL

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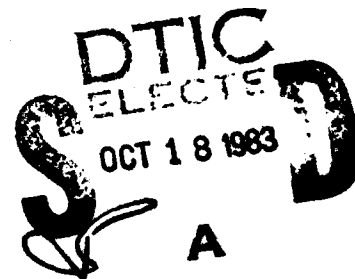
U.S. Coast Guard Research and Development Center
Avery Point Groton, Connecticut 06340



SEPTEMBER 1982

FINAL REPORT

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16. Abstract An oil spill behavior model has been developed which describes the changing area, thickness and physical properties of spills of Prudhoe Bay Crude Oil, No. 2 fuel (home heating) oil and No. 4 (heavy) fuel oil under Arctic marine conditions. The oil properties calculated are density, viscosity, pour point, aqueous solubility, flash point, fire point and interfacial tension. The model calculations include spreading into thin (sheen) and thick slicks, drift, evaporation, dispersion, and formation of water-in-oil emulsions (mousse formation). The model was calibrated by fitting the model equations to data obtained from outdoor weathering experiments conducted at the Coast Guard R&D Center, Groton, Connecticut, during the Winters of 1979/80 and 1980/81 in which arctic spring conditions were simulated. A comprehensive sampling program yielded data on the changing oil properties. The model successfully described the rate of evaporation and the physical properties under these test conditions, with the exception that interfacial tensions were not well predicted. This exception is probably due to the formation of surface active compounds by oil oxidation, and water-in-oil emulsion formation induced by rainfall. It is believed that the model provides the capability of predicting, with acceptable accuracy, the behavior and properties of the three oils when spilled under arctic marine conditions.			
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	* 2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (WEIGHT)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (EXACT)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price \$2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (WEIGHT)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (EXACT)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

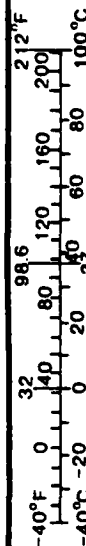


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LIST OF SYMBOLS

γ	interfacial tension (dyne/cm)
X	semi-major drop axis (cm)
r	radius of drop sphere (cm)
ω	angular velocity (s^{-1})
$\Delta\rho$	density difference between oil and water (g/cm^3)
N	evaporation rate (m^3/s)
K	mass transfer coefficient (m/s)
A	oil area (m^2)
P	oil vapor pressure (atm)
v	oil liquid molar volume ($m^3/mole$)
v_6	oil liquid molar volume at environmental temperature
v_{22}	oil liquid molar volume at $22^\circ C$
R	universal gas constant (82×10^{-6} at atm $m^3/mole K$)
T	absolute temperature (K)
K_n	calibration constants for physical properties
F_v	volume fraction evaporated
T_0	initial temperature (K)
T_B	boiling point temperature (K)
A_n, B_n	calibration constants for boiling point distillation
T_E	enviromental temperature (K)
P_E	oil vapor pressure at environmental temperature (atm)
ρ_E	density at environmental temperature (g/cm^3)
P_{22}	vapor pressure at $22^\circ C$ (atm)
ρ_{22}	density at $22^\circ C$ (g/cm^3)
V_0	initial volume of spilled oil (m^3)
t	time
θ	evaporative exposure

ABBREVIATIONS

m	= meters
cm	= centimeters
mL	= milliliters
kg	= kilogram
cp	= centipoise
Pas	= Pascal-seconds
mPas	= milli-Pascal-seconds
°C	= degrees Centigrade
mg	= milligram
ppm	= part per million
s	= seconds
g	= grams
mN	= milli-Newtons
μL	= microliter
min	= minutes
L	= liters
atm	= atmospheres
K	= degrees - Kelvin
mol	= mole

SUMMARY

An oil spill behavior model has been developed which describes the changing area, thickness and physical properties of spills of Prudhoe Bay Crude Oil, No. 2 fuel (home heating) oil and No. 4 (heavy) fuel oil under Arctic marine conditions. The oil properties calculated are density, viscosity, pour point, aqueous solubility, flash point, fire point and interfacial tension. The model calculations include spreading into thin (sheen) and thick slicks, drift, evaporation, dispersion, and formation of water-in-oil emulsions (mousse formation). The model was calibrated by fitting the model equations to data obtained from outdoor weathering experiments conducted at the Coast Guard R&D Center, Groton, Connecticut, during the Winters of 1979/80 and 1980/81 in which arctic spring conditions were simulated. A comprehensive sampling program yielded data on the changing oil properties. The model successfully described the rate of evaporation and the physical properties under these test conditions, with the exception that interfacial tensions were not well predicted. This exception is probably due to the formation of surface active compounds by oil oxidation, and water-in-oil emulsion formation induced by rainfall. It is believed that the model provides the capability of predicting, with acceptable accuracy, the behavior and properties of the three oils when spilled under arctic marine conditions.

1.0 INTRODUCTION

There is an obvious incentive to develop a capability to predict the extent of weathering of an oil spill under Arctic conditions, and the resulting changes in the oil's physical and chemical properties. These properties influence both oil behavior, such as spreading, and the applicability and effectiveness of the various available countermeasures. The ultimate objective is to be able to respond rapidly in the event of an Arctic oil spill. A computer program which calculates oil property changes as a result of receiving input data on the oil's properties and amount, and the environmental conditions, would assist this objective.

Many oil spill models have been developed to assist with countermeasures, most being of the trajectory type in which the aim is to calculate where the oil may be at any time. Such models essentially add wind and current vectors for selected time steps. In the model described here, the aim is to predict property changes rather than location, thus the model is complementary to a trajectory model. It may be wholly or partly incorporated into a trajectory model if desired.

It is also obvious that some set of oil property measurements should be made to permit rates of processes such as evaporation to be calculated. The algorithms or equations for such calculations are not always available and of a form compatible with the data acquired or with the oil spill model. These algorithms usually arise from controlled laboratory or outdoor experiments in which the rate of a process is studied in isolation.

In this work, we have addressed the problem of integrating information from (i) physical and chemical property measurements
(ii) outdoor evaporation experiments
(iii) recently developed algorithms describing oil spill processes

into a comprehensive oil spill behavior model.

Components (i) and (iii) relied heavily on previous work undertaken at the University of Toronto with Environment Canada (Arctic Marine Oilspill Program) support as described in several contract reports, notably Mackay and Paterson (1980), Mackay (1978) and Mackay, Buist, Mascarenhas, and Paterson (1979). Measurement and correlation of physical properties were made at the University of Toronto. Component (ii) was undertaken at the U.S. Coast Guard R&D Center, Groton, CT. A final integrating effort involved joint analysis of the results and formulation of the oil spill behavior model.

Three oils were tested both in the laboratory and at Groton; home heating or No. 2 fuel oil, heavy or No. 4 fuel oil, and Prudhoe Bay crude oil. These oils were selected by the U.S. Coast Guard as being representative of oil types most likely to be encountered in spill situations in offshore Alaska.

The approach taken in this report is to first describe in Section 2.0 the oil spill model (a complete listing being given in Appendix A). The experimental weathering work and the physical/chemical determinations are described in Section 3.0 and the results in Section 4.0. The calibration and a discussion of the results are given in Section 5.0.

2.0 OIL SPILL MODEL

Oil spill models are of two general types; trajectory models in which the aim is to predict the location and size of a slick in a given geographical setting under the influence of prevailing wind and current vectors, and behavior models in which the properties of the oil are predicted in some detail from a knowledge of the oil composition and environmental conditions, especially temperature and wind speed. These models may become computationally complex and rarely are they combined. A recent comprehensive review of the status of models has been prepared by Huang and Monastero (1980). Several models are described in the proceedings edited by Mackay and Paterson (1980). Valuable reviews of models and their component processes have been provided by Jordan and Payne (1980).

Possibly the most advanced models currently available or under development are those developed for the U.S. National Oceanic and Atmospheric Administration including recent work on their behalf by Science Applications, Inc., Kirstein and Payne (1982).

To be useful, a model must be applicable to different oils, preferably by inserting a number of parameters into the program which characterize such things as evaporation and changes in properties such as density as a function of extent of weathering and temperature. The model equations should minimize risk of computational failure. The number of parameters should be minimized and the inherent assumptions should be apparent to the user. These requirements favor simplicity but not at the cost of loss of realism. The model described here represents an attempt to achieve this goal by modifying and updating a model developed for the Environment Canada Arctic Marine Oilspill Program (AMOP) in 1975-1980 and most recently described by Mackay and Paterson (1980).

A complete printout of the model is given in Appendix A with behavior and property parameters defined individually for Prudhoe Bay crude oil, home heating oil and heavy fuel oil. The principal features of the model are described below.

The program is written in FORTRAN. It commences by setting spill conditions of oil volume and the duration of the release. Provision for instantaneous or continuous releases is available. Environmental conditions of temperature, wind speed and sea state are defined. The oil properties are entered in the form of appropriate constants for the equations tabulated later.

Rate constants for dispersion, emulsification, spreading, drift and evaporation are calculated or entered. Provision is made to allow any process to be stopped in order to explore its effect by comparing "with" and "without" outputs.

The initial oil properties and spill thickness are set and the calculation proceeds in time increments by computing the amount of oil evaporated and dispersed, water uptake which forms water-in-oil emulsions, spreading and drift. A complete printout then follows giving the mass balance, the rates of the processes and the newly computed oil properties which have changed as a result of evaporation. Any new oil is then added (if the spill is continuous) and the calculation repeated.

The oil is assumed to spread into a thin sheen surrounding thicker patches. Most of the spill area (e.g., 70 to 90%) is sheen, but most of the oil volume is contained in the thick patches. Equations are given to calculate the increase of the thick and sheen areas during a time increment. Provision is made for the thick slick to "feed" the thin slick, a process which is observed on the ocean surface. The spreading equations have been described by Mackay, Buist, Mascarenhas and Paterson (1979).

The evaporation calculation uses the "evaporative exposure" concept in which the oil's vapor pressure is first calculated as a function of temperature and fraction evaporated, then the amount evaporated calculated from a conventional mass transfer flux equation. Separate calculations are included for sheen and thick slicks. The physical basis for these equations has been described by Mackay, Paterson and Nadeau (1980) and by Mackay and Stiver (in preparation).

Dispersion rates for thick and sheen slicks are calculated as a function of windspeed and oil-water interfacial tension and are a simplification of equations described earlier by Mackay and Paterson (1980).

Emulsion (mousse) formation is included using the equations outlined by Mackay and Zagorski (1982). The water content and viscosity of the oil are calculated.

Finally, the location and shape of the slick are calculated using a drift factor of 3.5% of the wind speed. It is possible to overlay the slick location and size in a hydrographic chart.

The variables used in the program are defined and units given in most cases by comment cards in the program but additional information is provided in Appendix A.

A specimen output of the state of spill of Prudhoe Bay crude oil is given in Table 2.1.

Table 2.1 Specimen Output for State of Spill - Prudhoe Bay Crude

[illegible]

3.0 EXPERIMENTAL PROCEDURES

3.1 Weathering Experiment

A laboratory-scale outdoor experiment was conducted at the Coast Guard R&D Center during the Winters of 1979/80 and 1980/81 to simulate the weathering of oil under arctic conditions. Four oils were weathered outdoors on water in open boxes under natural environmental conditions for periods of up to a month with periodic sampling. Temperature and wind speed were monitored continuously to allow calculation of hourly "evaporative exposure" values. Solar radiation was also monitored to elucidate its effect on increasing the oil temperature.

The primary objective of the experiment was to document the effect of evaporation on oil weathering under cold conditions, and its role in determining the oil fraction remaining, and the physical and chemical properties of the oil. Of particular interest to the Coast Guard with regard to the physical properties were the density, viscosity, and combustibility of the oil, as these properties are likely to dictate the effectiveness of various cleanup measures such as skimming, use of suction hoses and burning.

A second objective was to determine the dependence of the rate of evaporation on the "evaporative exposure" and to verify the accuracy of the empirical formulations for modelling this dependence.

A third objective of the experiment was to investigate the dependence of the oil/air interface temperature on the air temperature, underlying surface temperature, and solar radiation. Of particular interest was the role of the solar radiation in raising the temperature of darker oils above ambient environmental levels.

This report deals with the first and second objectives as described above. The results stemming from the third objective are discussed in a separate Coast Guard R&D Center Report (Tebeau, Meehan, and Myers, 1982).

The oil weathering experiments were carried out on the roof of the main R&D Center building at Avery Point, Groton, CT. This location offered a marine environment with ample exposure to the elements. It was hoped that during the winter months, this environment would approximate conditions on the North Slope of Alaska during late spring and summer, when large quantities of oil would most likely reach the ice surface.

The experimental apparatus consisted of plywood weathering boxes (60 cm x 60 cm x 30 cm deep) lined with 5 cm of styrofoam insulation and fitted with a polyethylene liner to make the boxes reusable. Transparent covers were also fabricated and mounted 35 cm above the oil so that the weathering oil samples could be protected from rain and snow if desired as shown in Figures 3.1 and 3.2.

The experimental procedure called for freezing a block of fresh water ice in each box in the R&D Center cold room. The boxes were then transported to the roof where a 400 mL sample of the oil was deposited on the ice surface. The No. 2 and No. 4 oils were obtained from local University of



Figure 3.1 Photograph showing oil weathering experiment test site on the roof of the R&D Center.



Figure 3.2 Photograph showing the oil weathering box with oil sample and rain screen in place.

Connecticut physical plant stocks at Avery Point. The Prudhoe Bay crude oil was obtained by courtesy of the Atlantic Richfield Company. In warmer weather, the oil was initially deposited in a (30 cm x 30 cm) cavity chipped in the center of the ice block to prevent it from running down the sides of the block. Usually after a few days, enough melt water was present so that the oil covered most of the surface area inside the box. The oil samples were then allowed to weather for periods ranging from approximately 1 day to 1 month. At specified times during the period, a sample of each type of oil was removed from the weathering boxes. Descriptions of the environmental monitoring instrumentation are described by Tebeau, Meehan, and Myers (1982).

Altogether, 109 weathered oil samples (30 No. 2 oil, 31 No. 4 oil, 35 Prudhoe Bay Crude, and 13 No. 6 oil) were collected and analyzed for the Winter 1979/80 and Winter 1980/81 experiments. In addition, unweathered standard samples of each type of oil were taken at intervals throughout the experiment period. The time weathering began, time weathering ended, duration of weathering in hours, average temperature during the weathering period, average wind speed during the weathering period, and cumulative evaporative exposure for each weathered sample were calculated, the results being tabulated in Section 4.1.

A preliminary physical properties analysis was conducted at the Coast Guard R&D Center to check mass fraction remaining, specific gravity, viscosity, water content, flash point, fire point, and combustibility. Chemical analysis at the R&D Center involved running Gas Chromatograph (GC) scans on each sample to delineate its chemical composition. A complete description of this analysis and the results are given in a companion report by Tebeau, Meehan, and Myers (1982). Based on the initial results of the R&D Center analysis, various samples of the No. 2 oil, No. 4 oil, and Prudhoe Bay crude oil were selected for further analysis by the University of Toronto as described in Section 2.0. It is the result of this more detailed analysis that forms the basis of the model calibration effort described in Section 5.0.

3.2 Physical Property Determination

Detailed analyses were conducted on 13 samples of Prudhoe Bay crude oil (designated by a prefix "PBC"), 13 samples of home heating oil (HH), and 13 samples of heavy fuel oil (FO), most obtained from the outdoor weathering experiment at Groton. The remainder were samples of the fresh oils and oils obtained by artificial weathering in the laboratory (designated AB). The artificially weathered samples were prepared by bubbling a stream of air of known flow rate through a volume of oil for specified times generally following the procedure described by Mackay and Stiver (1982). This latter group of samples gave results which were used to develop equations describing the physical properties as a function of temperature and extent of evaporation. The equations were then tested on the Groton samples.

Density

Density was measured at 0°C and 20°C using a standard pycnometer calibrated with distilled water. The results are presented in units of kg/m³. Specific gravity is thus this number divided by 1000.

Pour Point

Pour points were measured using the standard American Society for Testing Materials-Institute of Petroleum Method #D97. The general procedure was to heat the oil sample to approximately 46°C, then cool the sample steadily with cold water, then ice water, then an acetone-dry ice mixture (as necessary) until a temperature is reached at which the oil in the test vessel does not flow when tilted horizontally. The results are expressed in °C.

Viscosity

Viscosities were measured using a standard Canon Fenske viscometer at 0°C, 10°C, 20°C, the results being reported in units of centipoise (cp). The now-standard unit is Pascal-seconds (Pas), 1 Pas corresponding to 1000 cp or 1 milli-Pas (mPas) to 1 cp. In most cases, it was either not necessary or it was impossible to measure viscosities at all the above temperatures. For example, it is not feasible to measure viscosities below the pour point, thus the Prudhoe Bay samples which had pour points in the range -2 to +18°C were examined at 10 and 20°C or 20 and 30°C. Only two determinations are necessary to obtain information about the temperature dependence of viscosity.

Aqueous Solubility

Approximately 5-10 mL of the oil samples were added to a separatory funnel containing 50-100 mL of double distilled water. The separatory funnels were shaken gently in a wrist action shaker for about two hours and then allowed to settle for at least 48 hours before analysis at 20°C. 2-3 mL of the saturated aqueous solution were drawn to be analyzed by "purge-and-trap" gas chromatography. The results are given in g/m³ which is numerically equal to mg/L or ppm.

The gas chromatograph was a Hewlett-Packard Model 5840 equipped with a flame ionization detector and a Model 7675A purge-and-trap sampler. The GC column was a wide bore 50 meter long glass capillary column coated with SE-30 (WCOT from Alltech Associates, Inc.).

Typical chromatograms of the fresh oils and field samples are shown in Section 4.0. It was noted that the dissolved components were mostly aromatic in nature, e.g., benzene, toluene, xylenes, substituted benzenes and naphthalenes which is expected as their solubilities in water are higher than those of alkanes. The solubilities were determined using benzene for calibration purposes. As the oil weathered, its solubility decreased leaving the higher molecular weight components such as polynuclear aromatics in the solution. Since the solution was purged at room temperature, it was impossible to strip hydrocarbons heavier than n-C₁₆ or naphthalene from the water.

This is not regarded as a serious problem because these hydrocarbons have low solubilities and they will contribute little in addition to the measured solubility.

It should be noted that these solubilities are measured in distilled water, not seawater. It is, however, relatively simple to calculate the seawater solubility from that of distilled water, the seawater value generally being 75% of the distilled water value.

Oil-Water Interfacial Tension

Oil-water interfacial tension was measured by the spinning drop technique at 20°C in which the shape of an oil drop is observed while spinning in a horizontal column of synthetic seawater (35 g/L sodium chloride), centrifugal effects causing the oil to locate along the axis. The oil drop adopts a nearly cylindrical shape with the relative length and diameter controlled by the balance between centrifugal forces (which tend to elongate the drop) and interfacial tension forces (which tend to favor area reduction and thus resist elongation). By measurement of droplet volume and length at known spinning frequency, it is possible to calculate the interfacial tension, if phase density information is known. The technique has been described by Mackay and Hossain (1982) who give the equations which are used in this work, namely,

$$(1/\gamma)^{1/3} (3X/2)(H)^{1/3} = H r^3/\gamma + 1$$

$$\text{where } H = \frac{\Delta\rho\omega^2}{4}$$

and γ is interfacial tension (dynes/cm), X is semi-major drop axis (cm), i.e., half the length, r is the radius of the drop sphere of equivalent volume (cm), ω is angular velocity (s^{-1}), and $\Delta\rho$ is density difference between oil and water (g/cm^3). The equation is solved iteratively for γ .

The calculation if done in SI units gives interfacial tension in Newtons/meter (N/m). The commonly used CGS unit of 1 dyne/cm is 10^{-3} N/m or 1 milli-Newtons/meter (mN/m). An advantage of the technique is that there is no solid surface in contact with the oil as occurs in the pendant, sessile drop, or de Nouy ring tests.

For selected samples of low viscosity, oil-air interfacial tensions were also measured at 20°C (using the de Nouy ring method).

Oil sheen spreading properties are influenced by these interfacial tensions, the net spreading tendency (ST) being given by

$$ST = \gamma_{AW} - \gamma_{OW} - \gamma_{OA}$$

where the interfacial tensions (γ) are subscripted AW (air/water interface), OW (oil/water interface) and OA (oil/air interface). A positive value of ST results in spreading.

Gas Chromatographic Analysis

To estimate the fraction of the oil which had evaporated, GC analyses were done and the traces compared with samples which had been evaporated to known extents.

A 0.5 μ L sample was injected into a Hewlett-Packard Model-5750 gas chromatograph. The column was temperature programmed from 50°C to 280°C at 15 degrees/min with a one-minute post injection interval. The column used was a 10 foot long, 1/8 inch O.D. stainless steel column, coated with 10% SE30 ultraphase on chromosorb P, A/W, DMCS, mesh 60/80. A flame ionization detector was maintained at 320°C and the injection port was held at 300°C. The carrier gas and the hydrogen flow rate were at about 30 mL/min. The air flow rate was 500 mL/min. A Shimadzu C-RIA Chromatopac integrator recorder was used.

The fuel oil samples which were much less volatile were analyzed in the same manner using a HP 700 Laboratory Chromatograph.

Laboratory Evaporation (Air Bubbling)

To prepare oil samples of known extents of evaporation, oils were subjected to air bubbling under controlled flow and temperature conditions. This gives data which can be used to estimate environmental weathering.

In addition, samples of this "artificially weathered" oil were taken and selected properties determined; namely, the distillation curves and other property curves discussed earlier.

The oils were air bubbled in a 250 mL graduated cylinder. The small cylinder size forced the use of low air flowrates, generally in the range of 1 L/min. The oil was evaporated for selected "exposures" to obtain evenly spaced samples.

To take each sample, the cylinder mass and the volume of oil at both 0°C and 20°C were measured and approximately 40 mL was poured into the pour point apparatus. This 40 mL was used for all the remaining tests. The cylinder was then reweighed and the volume of oil was measured at 20°C only. At this point the amount of air which passed through the oil was recorded.

In the case of the home heating oil there was an accidental loss of approximately 60 mL during the experiment. Fortunately, there was still sufficient oil remaining to complete the experiment.

Distillation

The distillation method used (which gives oil volatility data) is not the ASTM method. The process used was altered in order to predict the evaporation rate more accurately. This is done by measuring the liquid's boiling temperature not the lower condensing vapor temperature. The flask from which the oil was boiled was insulated to reduce superheating, and the liquid contained glass beads (or boiling chips) and a magnetic stirrer to maintain uniformity. A thermocouple was used to measure the liquid temperature.

The amount of condensing liquid was measured against boiling temperature. Precautions were taken to prevent the evaporation of the liquid once it reached the end of the distillation column.

Flash and Fire Points

Flash and fire points were measured for selected oil samples to provide an indication of the ease of ignition. The standard ASTM Cleveland Open Cup method was used and the results reported in °C.

Emulsion Stability

The wax and asphaltene contents of the fresh oils were also measured as mass fractions by standard methods. Assuming that these components do not evaporate, the values for evaporated oils could be calculated readily. These quantities are used later in estimating stability of water-in-oil emulsions as described by Mackay and Zagorski (1982).

In addition, the fresh oils were subjected to a recently developed emulsion formation and stability test described by Mackay and Zagorski (1982).

In total, this work gave a comprehensive set of data which could be used to develop expressions relating the properties as discussed in Section 5.0.

4.0 RESULTS

4.1 Weathering Experiments

The time of year during which the samples were weathered, the condition of the underlying surface, and the prevailing weather conditions during certain weathering periods have led to specific groupings of the samples for the various types of oil as outlined below:

<u>Group</u>	<u>Weathering Period</u>	<u>Samples</u>
<u>Prudhoe Bay Crude</u>		
Winter 1980	4 Feb - 22 Feb 1980	1 - 8
Winter 1981	1 Dec - 4 Feb 1980	9 - 18
Winter 1981 (emulsified)	3 Feb - 26 Feb 1981 and 10 Mar - 13 Apr 1981	19 - 25 and 34 - 35
Spring 1981	2 Mar - 30 Apr 1981	26 - 33
<u>No. 2 Home Heating Oil</u>		
Winter 1980	11 Feb - 25 Feb 1980	1 - 7
Winter 1981	6 Jan - 25 Feb 1981	8 - 18
Spring 1981	26 Feb - 10 Mar 1981	19 - 30
<u>No. 4 Fuel Oil</u>		
Winter 1980	18 Feb - 6 Mar 1980	1 - 6
Winter 1981	6 Jan - 4 Feb 1981	7 - 14
Winter 1981 (emulsified)	3 Feb - 26 Feb 1981 and 2 Mar - 6 Apr 1981	15 - 21 and 25,27,29,30
Spring 1981	2 Mar - 13 Apr 1981	22-24,26,28,31

Tables 4.1 and 4.3 give start and end times, duration, average temperature, wind speed, and evaporative exposure (θ) for each sample. θ , the evaporation exposure, is calculated as KAt/V_o where

K is the mass transfer coefficient calculated from the wind speed (U (m/s)) by $K = 0.0025 U^{0.78}$ (Mackay and Matsugu, 1973)

A is the oil area (m^2)

t is time (s)

V_o is the initial volume of spilled oil (m^3)

The first (Winter 1980) group of samples were weathered during cold weather in February-March 1980 when the ice blocks were generally intact and air temperatures were generally below freezing. The samples were covered with the transparent covers to protect them from precipitation. These samples were initially deposited in cavities in the ice so that the spill area was generally less than the box area for the first few days. Although these samples started out on a solid ice surface, by the end of the period some melting had occurred so that a simulated melt pond situation existed.

The second (Winter 1981) group contains those samples which were weathered during very cold weather in January 1981 for the most part on a solid ice surface. They were not initially deposited in a cavity so that the oil covered the major portion of the box area. The samples were not sheltered by the plastic screens so that snow was allowed to accumulate on the samples. This led to some interesting observations of oil/snow/ice interaction for the darker oils (No. 4 and Prudhoe Bay crude) when solar radiation and warmer temperatures melted the snow. It appears that the darker oils are initially sheltered from the atmosphere by the snow. As solar radiation warms the snow and the oil underneath, the oil appears to pocket in small depressions in the snow and ice (up to a few cm in diameter) (Figures 4.1 and 4.3). It is quite possible that this initial sheltering followed by the collection of the oil into small pockets with a local increase in slick thickness may have a significant short-term effect on the weathering rate. The lighter No. 2 home heating oil did not show this pocketing tendency. It saturated the snow evenly shortly after being covered.

The third group of samples (Winter 1981 emulsified), refer primarily to those samples that were weathered during February 1981. These samples were deposited in 30 cm x 30 cm cavities in the ice to prevent runoff during a warming period in February 1981. The samples were not covered with the transparent screens. Melt pond conditions prevailed throughout the period. During the night of 7-8 February, heavy rains fell inundating the samples. Although the samples remained intact with little oil loss, some oil emulsification was immediately noticed. The emulsification significantly affected the physical properties and possibly the weathering rates of the samples. Accordingly, some of the later samples (March-April 1981) which showed indications of emulsification are also included in this group.

Table 4.1 Exposure Conditions - Prudhoe Bay Crude.

#	SAMPLE	START TIME/DATE	END TIME/DATE	HOURS	AVERAGE TEMP DEG C	AVERAGE WIND M/SEC	EVAP EXPOSURE X 10 ⁻⁶
01	PBC #01	1000 04 FEB 80	0900 05 FEB 80	024	-1.2	3.0	.449
02	PBC #02	1000 04 FEB 80	0900 06 FEB 80	048	-5.2	2.9	.337
03	PBC #03	1000 04 FEB 80	0900 08 FEB 80	096	-3.0	3.3	1.947
04	PBC #04	1000 04 FEB 80	0900 11 FEB 80	170	-2.2	3.0	3.138
05	PBC #05	1000 04 FEB 80	0900 19 FEB 80	360	-1.7	3.4	7.335
06	PBC #06	1000 04 FEB 80	0900 03 MAR 80	672	-1.4	3.2	13.071
07	PBC #07	1200 20 FEB 80	0900 21 FEB 80	021	3.2	1.1	.185
08	PBC #08	1200 20 FEB 80	1400 22 FEB 80	050	4.0	2.1	.707
09	PBC #09	1100 01 DEC 80	1000 02 DEC 80	023	-13.4	2.1	.320
10	PBC #10	1100 01 DEC 80	1000 03 DEC 80	047	-13.3	4.0	1.068
11	PBC #11	1400 06 JAN 81	1300 08 JAN 81	047	-3.3	4.1	1.134
12	PBC #12	1400 06 JAN 81	0800 10 JAN 81	090	-5.9	3.0	1.645
13	PBC #13	1400 06 JAN 81	0900 12 JAN 81	139	-8.1	3.2	2.730
14	PBC #14	1400 06 JAN 81	0900 15 JAN 81	211	-8.6	2.8	3.673
15	PBC #15	1400 06 JAN 81	1000 19 JAN 81	308	-7.5	2.8	5.450
16	PBC #16	1400 06 JAN 81	0900 22 JAN 81	379	-6.4	2.6	6.325
17	PBC #17	1400 06 JAN 81	0900 29 JAN 81	547	-4.3	2.6	9.090
18	PBC #18	1400 06 JAN 81	0900 04 FEB 81	691	-4.0	2.8	12.072
19	PBC #19	0900 03 FEB 81	0900 05 FEB 81	048	-8.2	3.0	.896
20	PBC #20	0900 03 FEB 81	0900 09 FEB 81	144	-3.7	2.9	2.631
21	PBC #21	0900 03 FEB 81	0900 12 FEB 81	216	-1.6	3.7	4.685
22	PBC #22	0900 03 FEB 81	0900 17 FEB 81	336	-1.6	3.2	6.474
23	PBC #23	0900 03 FEB 81	0900 19 FEB 81	384	-7	3.1	7.189
24	PBC #24	0900 03 FEB 81	0900 23 FEB 81	480	1.0	3.3	9.118
25	PBC #25	0900 03 FEB 81	0900 26 FEB 81	552	1.6	3.3	10.926
26	PBC #26	0900 02 MAR 81	0900 04 MAR 81	048	-4	3.4	1.011
27	PBC #27	0900 02 MAR 81	0900 09 MAR 81	168	1.0	2.9	3.042
28	PBC #28	0900 02 MAR 81	0900 12 MAR 81	240	1.5	2.8	4.250
29	PBC #29	0900 02 MAR 81	0900 16 MAR 81	336	1.8	3.5	7.071
30	PBC #30	0900 02 MAR 81	0900 19 MAR 81	408	1.2	3.7	8.329
31	PBC #31	1100 10 MAR 81	0900 23 MAR 81	310	1.0	3.8	6.895
32	PBC #32	1100 10 MAR 81	0700 26 MAR 81	380	1.4	3.4	7.651
33	PBC #33	1100 10 MAR 81	0700 30 MAR 81	476	2.3	3.4	9.713
34	PBC #34	1100 10 MAR 81	0800 06 APR 81	645	4.3	3.5	13.605
35	PBC #35	1100 10 MAR 81	0700 13 APR 81	811	5.1	3.6	17.443
36	PBC ST1	---	---	000	---	---	0.000
37	PBC ST2	---	---	000	---	---	0.000
38	PBC ST3	---	---	000	---	---	0.000

Table 4.2 Exposure Conditions - No. 2 Home Heating Oil.

#	SAMPLE	START TIME/DATE	END TIME/DATE	HOURS	AVERAGE TEMP DEG C	AVERAGE WIND M/SEC	EVAP EXPOSURE X 10 ⁻⁶
01	No2 #01	1000 11 FEB 80	0900 12 FEB 80	023	-.2	4.2	.559
02	No2 #02	1000 11 FEB 80	1000 13 FEB 80	048	-.8	3.5	1.021
03	No2 #03	1000 11 FEB 80	1000 15 FEB 80	101	-3.2	3.5	2.105
04	No2 #04	1000 11 FEB 80	1400 18 FEB 80	172	-1.4	3.5	3.582
05	No2 #05	1000 11 FEB 80	0900 25 FEB 80	335	.7	3.0	6.219
06	No2 #06	1000 11 FEB 80	SAMPLE LOST	000	---	---	0.000
07	No2 #07	1200 20 FEB 80	1400 21 FEB 80	026	4.1	1.5	.278
08	No2 #08	1400 06 JAN 81	1300 07 JAN 81	023	.4	4.0	.547
09	No2 #09	1400 06 JAN 81	0800 10 JAN 81	090	-5.9	3.0	1.545
10	No2 #10	1400 06 JAN 81	0900 12 JAN 81	139	-8.1	3.2	2.730
11	No2 #11	1400 06 JAN 81	0900 15 JAN 81	211	-8.6	2.8	3.693
12	No2 #12	1400 06 JAN 81	1000 19 JAN 81	308	-7.5	2.8	5.450
13	No2 #13	1400 06 JAN 81	0900 22 JAN 81	379	-6.4	2.6	6.325
14	No2 #14	1400 06 JAN 81	0900 29 JAN 81	547	-4.3	2.6	9.090
15	No2 #15	1400 06 JAN 81	0900 04 FEB 81	691	-4.0	2.8	12.072
16	No2 #16	0900 03 FEB 81	0900 05 FEB 81	048	-8.2	3.0	.896
17	No2 #17	0900 03 FEB 81	0900 09 FEB 81	144	-3.7	2.9	2.631
18	No2 #18	0800 25 FEB 81	1600 25 FEB 81	008	5.0	4.2	.200
19	No2 #19	1100 10 MAR 81	0900 11 MAR 81	022	2.9	2.1	.305
20	No2 #20	1100 10 MAR 81	0900 12 MAR 81	046	2.4	2.7	.787
21	No2 #21	1100 10 MAR 81	1100 14 MAR 81	096	3.2	4.1	2.250
22	No2 #22	1100 10 MAR 81	1100 16 MAR 81	144	2.6	4.4	3.633
23	No2 #23	1100 10 MAR 81	1200 18 MAR 81	193	1.5	4.5	4.951
24	No2 #24	1100 10 MAR 81	0900 19 MAR 81	214	1.1	4.4	5.366
25	No2 #25	1100 10 MAR 81	0700 30 MAR 81	276	.8	4.1	6.566
26	No2 #26	1100 10 MAR 81	0700 06 APR 81	644	4.3	3.5	13.584
27	No2 #27	1200 16 MAR 81	1100 19 MAR 81	071	-2.1	4.2	1.739
28	No2 #28	1200 16 MAR 81	0800 23 MAR 81	164	-.5	3.3	3.235
29	No2 #29	1200 16 MAR 81	0800 24 MAR 81	188	-.2	3.0	3.434
30	No2 #30	1200 16 MAR 81	0800 26 MAR 81	236	.6	2.7	4.016
31	No2 ST1	---	---	000	---	---	0.000
32	No2 ST2	---	---	000	---	---	0.000
33	No2 ST3	---	---	000	---	---	0.000

Table 4.3 Exposure Conditions - No. 4 Fuel Oil.

#	SAMPLE	START TIME/DATE	END TIME/DATE	HOURS	AVERAGE TEMP DEG C	AVERAGE WIND M/SEC	EVAP EXPOSURE X 10 ⁻⁶
01	No4 #01	1300 18 FEB 80	1300 19 FEB 80	022	.4	5.3	.645
02	No4 #02	1300 18 FEB 80	0900 20 FEB 80	042	.8	3.7	.906
03	No4 #03	1300 18 FEB 80	1200 22 FEB 80	093	2.8	2.7	1.579
04	No4 #04	1300 18 FEB 80	1400 25 FEB 80	167	3.0	2.5	2.677
05	No4 #05	1400 03 MAR 80	0900 05 MAR 80	043	2.1	3.0	.784
06	No4 #06	1400 03 MAR 80	1500 06 MAR 80	073	3.2	3.4	1.493
07	No4 #07	1400 06 JAN 81	1300 07 JAN 81	023	.4	4.0	.547
08	No4 #08	1400 06 JAN 81	0800 10 JAN 81	090	-5.9	3.0	1.645
09	No4 #09	1400 06 JAN 81	0900 12 JAN 81	139	-8.1	3.2	2.730
10	No4 #10	1400 06 JAN 81	0900 15 JAN 81	211	-8.6	2.8	3.693
11	No4 #11	1400 06 JAN 81	1000 19 JAN 81	308	-7.5	2.8	5.450
12	No4 #12	1400 06 JAN 81	0900 22 JAN 81	379	-6.4	2.6	6.325
13	No4 #13	1400 06 JAN 81	0900 29 JAN 81	547	-4.3	2.6	9.090
14	No4 #14	1400 06 JAN 81	0900 04 FEB 81	691	-4.0	2.8	12.072
15	No4 #15	0900 03 FEB 81	0900 05 FEB 81	048	-8.2	3.0	.396
16	No4 #16	0900 03 FEB 81	0900 09 FEB 81	144	-3.7	2.9	2.631
17	No4 #17	0900 03 FEB 81	0900 12 FEB 81	216	-1.6	3.7	4.685
18	No4 #18	0900 03 FEB 81	0900 17 FEB 81	336	-1.6	3.2	6.494
19	No4 #19	0900 03 FEB 81	0900 19 FEB 81	384	-.7	3.1	7.189
20	No4 #20	0900 03 FEB 81	0900 23 FEB 81	480	1.0	1.5	.418
21	No4 #21	0900 03 FEB 81	0900 26 FEB 81	552	1.6	3.3	10.726
22	No4 #22	0900 02 MAR 81	0800 04 MAR 81	048	-.4	3.4	1.011
23	No4 #23	0900 02 MAR 81	0900 09 MAR 81	168	1.0	2.8	3.042
24	No4 #24	0900 02 MAR 81	0900 12 MAR 81	240	1.5	2.8	4.250
25	No4 #25	0900 02 MAR 81	0900 16 MAR 81	336	1.5	3.5	7.071
26	No4 #26	0900 02 MAR 81	0800 19 MAR 81	408	1.2	3.7	8.829
27	No4 #27	1100 10 MAR 81	0800 23 MAR 81	310	1.0	3.8	6.095
28	No4 #28	1100 10 MAR 81	0700 26 MAR 81	380	1.4	3.4	7.651
29	No4 #29	1100 10 MAR 81	0700 30 MAR 81	476	2.3	3.4	9.713
30	No4 #30	1100 10 MAR 81	0800 06 APR 81	645	4.3	3.5	13.605
31	No4 #31	1100 10 MAR 81	0700 13 APR 81	811	5.1	3.6	17.443
32	No4 ST1	---	---	000	---	---	0.000
33	No4 ST2	---	---	000	---	---	0.000
34	No4 ST3	---	---	000	---	---	0.000



Figure 4.1 Photograph showing dark oil sample covered by layer of snow.



Figure 4.2 Photograph showing dark oil sample after snow has melted. Note depressions and pocketing of oil.



Figure 4.3 Photograph showing closeup of dark oil sample with oil pockets. Scale is in centimeters.

The fourth group (Spring 1981) consists of those samples which were weathered during March-April 1981 when warmer weather prevailed (daytime temperatures well above 0°C), and clear skies led to significant solar radiation levels at the test site. As periods of melting and rainfall were expected, the samples were deposited in the 30 cm x 30 cm cavities and covered with the transparent screens. These samples generally experienced a progression of underlying surface conditions as the ice blocks deteriorated. The samples would rest on solid ice for the first day or so, spread out as melt water created a melt pool situation after a few days, and eventually weather in open water about 20-30 cm deep as the ice block deteriorated completely. This hopefully simulated late summer conditions on the North Slope when accelerated weathering of a spill is likely to occur.

The No. 6 fuel oil samples were not separated into groups and were analyzed in only a cursory fashion, as very little weathering was observed. In fact, the No. 6 oil congealed into a semi-solid mass at the colder ambient temperatures on the roof and did not spread into a slick as did the other oils. When periods of warmer temperatures and increased solar radiation melted the ice around the oil, the semi-solid mass would become partially submerged in the melt water. If the melt water refroze, the oil mass would then be largely encapsulated in the ice, further sheltering the oil from the atmosphere. The fraction of oil remaining and density values for these samples confirmed the absence of any appreciable weathering.

4.2 Physical/Chemical Properties

The results of the physical properties analysis conducted for selected oil samples by the University of Toronto are given in Tables 4.4, 4.5, and 4.6 for the Prudhoe Bay crude oil, the home heating oil, and the heavy fuel oil. The distillation curves are presented in Figure 4.4. Gas chromatographic traces are given in Figures 4.5 to 4.10 for the fresh oil samples and for selected degrees of evaporation. Figure 4.11 illustrates the results obtained in the "purge and trap" analysis for water solubility. The emulsion stability test results are given in Table 4.7.

These results form the basis of the model calibration work described in Section 5.0. A more detailed discussion of the changes in physical and chemical properties with weathering, and the implications on oil spill countermeasures and cleanup is contained in the report by Tebeau, Meehan, and Myers (1982).

TABLE 4.4 ANALYTICAL RESULTS FOR PRUDHOE HAY CRUDE OIL.

Sample	Density kg/m ³		Pour Point	Viscosity cp or mPas			Aqueous Solubility At 20°C g/m ³	Interfacial Tension dynes/cm or N/m oil-water	Interfacial Tension oil-air	Estimated Volume Fraction Evaporated	Flash Point	Fire Point
	0°C	20°C		0°C	10°C	20°C						
PRC-02-A06-Fres	909	901	- 2	1500	96	34.9	29.2	27.0	30.1	0		
PRC-AB-A06-111	907	897	+ 4		180	56	25.06	32.2		0.040		
PRC-AB-A07-667	913	904	+ 8		290	91	9.23	33.1		0.092		
PRC-AB-A10-1770	922	911	+ 9		600	140	3.04	35.4		0.127		
PRC-AB-A12-7260	929	918	+ 9		560	220	0.81	37.1	33.8	0.179		
PRC-19-A07	934	920	+ 6		630	130	8.50	10.1		0.11 ± 0.01		
PRC-12-A10	936	931	+ 9		1600	200	4.28	10.8		0.135 ± 0.015	101	122
PRC-27-A10	944	933	+ 9		4000	300	1.93	1.66		0.18 ± 0.02		
PRC-21-A11	976	969	+12			2400	0.53	Difficult to measure		0.195 ± 0.015		
PRC-22-A11	983	977	+15			6000	0.30	Difficult to measure		0.225 ± 0.025		
PRC-29-A12	968	960	+12			1000	0.18	Difficult to measure		0.215 ± 0.035		
PRC-24-A13	989	981	+15			10000	0.15	Difficult to measure		0.245 ± 0.024		
PRC-35-A13	987	980	+18			9000	0.045	Difficult to measure		0.275 ± 0.025		
PRC-26											110	128
PRC-14											112	130
PRC-33											150	171

TABLE 4.5 ANALYTICAL RESULTS FOR HOME HEATING OIL.

Sample	Density kg/m^3		Pour Point	Viscosity cp or mPas			Aqueous Solubility At 20°C g/m^3	Interfacial Tension dynes/cm or mN/m oil-water	Estimated Volume Fraction Evaporated	Flash Point	Fire Point
	0°C	25°C		0°C	10°C	20°C					
III-07-A16-Fresh	869	860	-27	7.74		4.04	3.12	25.6	0	104	109
III-AB-A14-1530	840	830	-27	7.86		4.11	1.48	29.6	0.023		
III-AB-A17-4900	853	841	-21	8.69		4.37	1.27	32.3	0.052		
III-AB-A19-7900	852	845	-26	8.56		4.45	0.72	33.6	0.079		
III-AB-A21-9150	863	856	-26	9.53		4.71	0.70	33.9	0.099		
III-19-A16	853	841	-27	8.33		4.26	1.62	20.2	0.065 \pm 0.015		
III-20-A17	855	843	-27	8.87		4.68	0.76	2.9	0.075 \pm 0.015	107	116
III-08-A18	856	845	-26	9.56		4.93	0.73	3.5	0.105 \pm 0.015		
III-16-A18	855	843	-21	8.99		4.61	0.87	4.6	0.070 \pm 0.015	128	131
III-27-A18	856	845	-21	9.67		4.83	0.75	4.3	0.090 \pm 0.010		
III-28-A19	859	846	-27	11.3		5.55	0.31	4.3	0.160 \pm 0.06	123	131
III-30-A19	858	848	-21	12.6		5.92	0.28	4.4	0.200 \pm 0.05		
III-25-A19	861	848	-19	18.8		7.76	0.21	4.0	0.250 \pm 0.05		
III-10										108	114
III-21										107	113
III-22										115	121
III-24										125	132
III-14										110	115

TABLE 4.6 ANALYTICAL RESULTS FOR HEAVY FUEL OIL.

Sample	Density kg/m ³		Pour Point	Viscosity cp or mPas			Aqueous Solubility At 20°C g/m ³	Interfacial Tension dyne/cm or N/m oil-water oil-air		Estimated Volume Fraction Evaporated	Flash Point	Fire Point
	0°C	20°C		0°C	10°C	20°C						
FO-02-ST-A20	938	925	-3.0		47.2	22.7	6.46	30.23	32.1	0	78	84
FO-AB-A23-2300	923	909	+3.0		68.7	26.7	4.15	34.1		0.025		
FO-AB-A23-5250	924	914	+3.0		70.4	28.8	3.60	36.2		0.046		
FO-AB-A24-7440	926	916	+5.0		73.2	30.4	3.70	37.6	32.1	0.059		
FO-AB-A25-11300	936	922	+6.0		90.8	36.9	2.32			0.084		
FO-07-A20	943	932	0		70.3	30.1	4.22	22.3		0.050 ± 0.01	103	110
FO-22-A20	945	934	+3.0		167.	40.9	2.49	30.1		0.085 ± 0.015	108	117
FO-16-A20	954	941	+6.0		360.	78.8	1.43	23.6		0.125 ± 0.025		
FO-10-A20	960	945	+9.0			106.	2.58	24.5		0.100 ± 0.020	117	121
FO-12-A21	960	951	+12			194	1.74	24.8		0.200 ± 0.05	128	132
FO-20-A21	990	979	>46				0.25			0.250 ± 0.05		
FO-30-A21	992	984	+24				0.20	Difficult to measure		0.400 ± 0.10		
FO-14-A24	978	970	+18				0.69	Difficult to measure		0.300 ± 0.05	148	152
FO-15											98	102

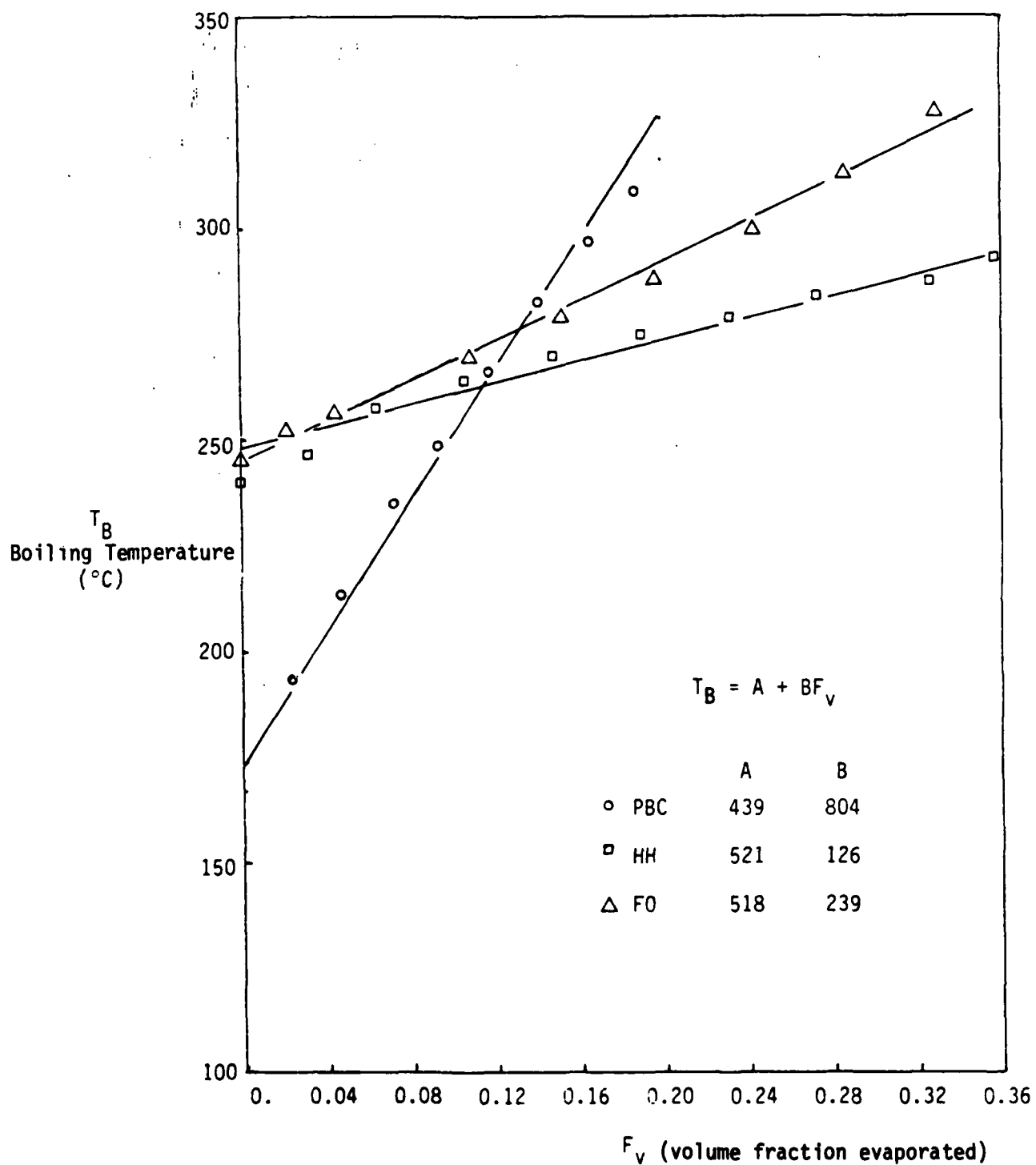


FIGURE 4.4. DISTILLATION CURVES

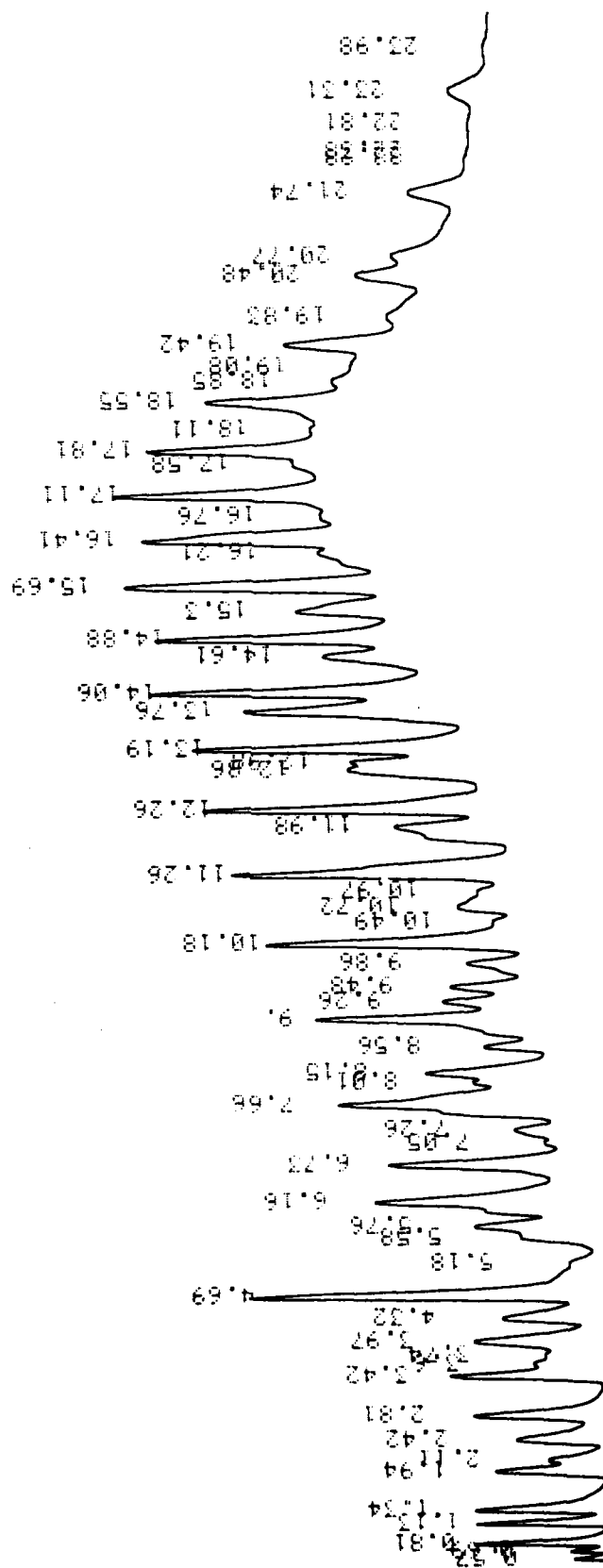


Figure 4.5 Gas chromatograph trace - Prudhoe Bay Crude---Fresh

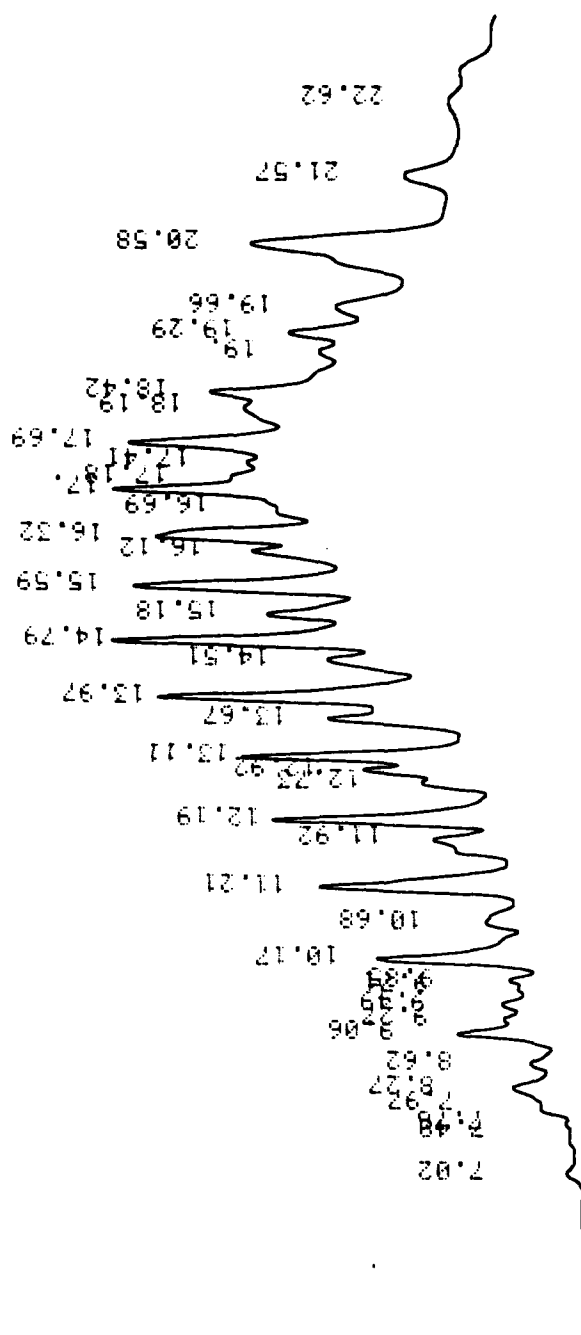


Figure 4.6 Gas chromatograph trace - Prudhoe Bay Crude--Weathered

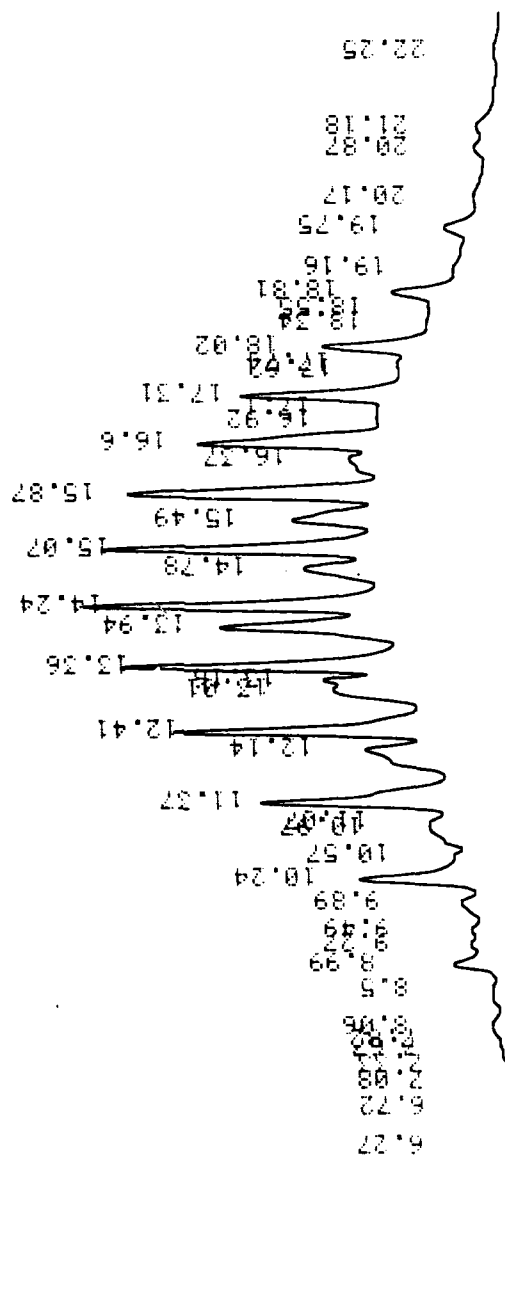


Figure 4.7 Gas chromatograph trace - No. 2 Home Heating Oil--Fresh

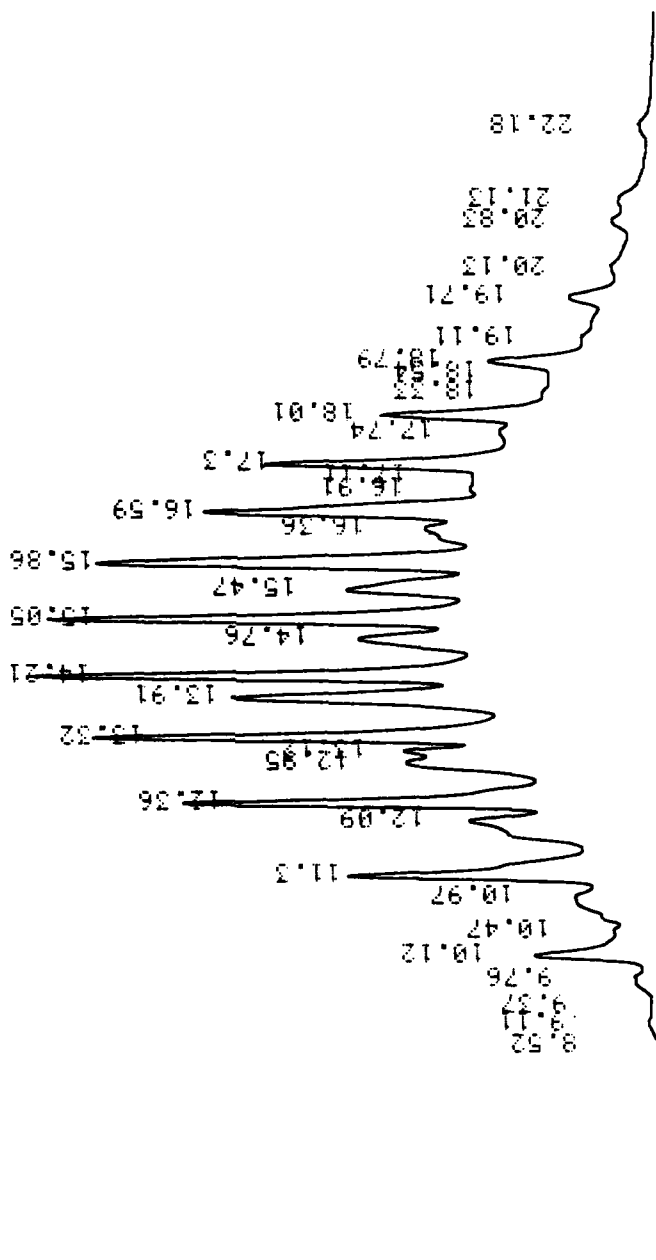


Figure 4.8 Gas chromatograph trace - No. 2 Home Heating Oil--Weathered

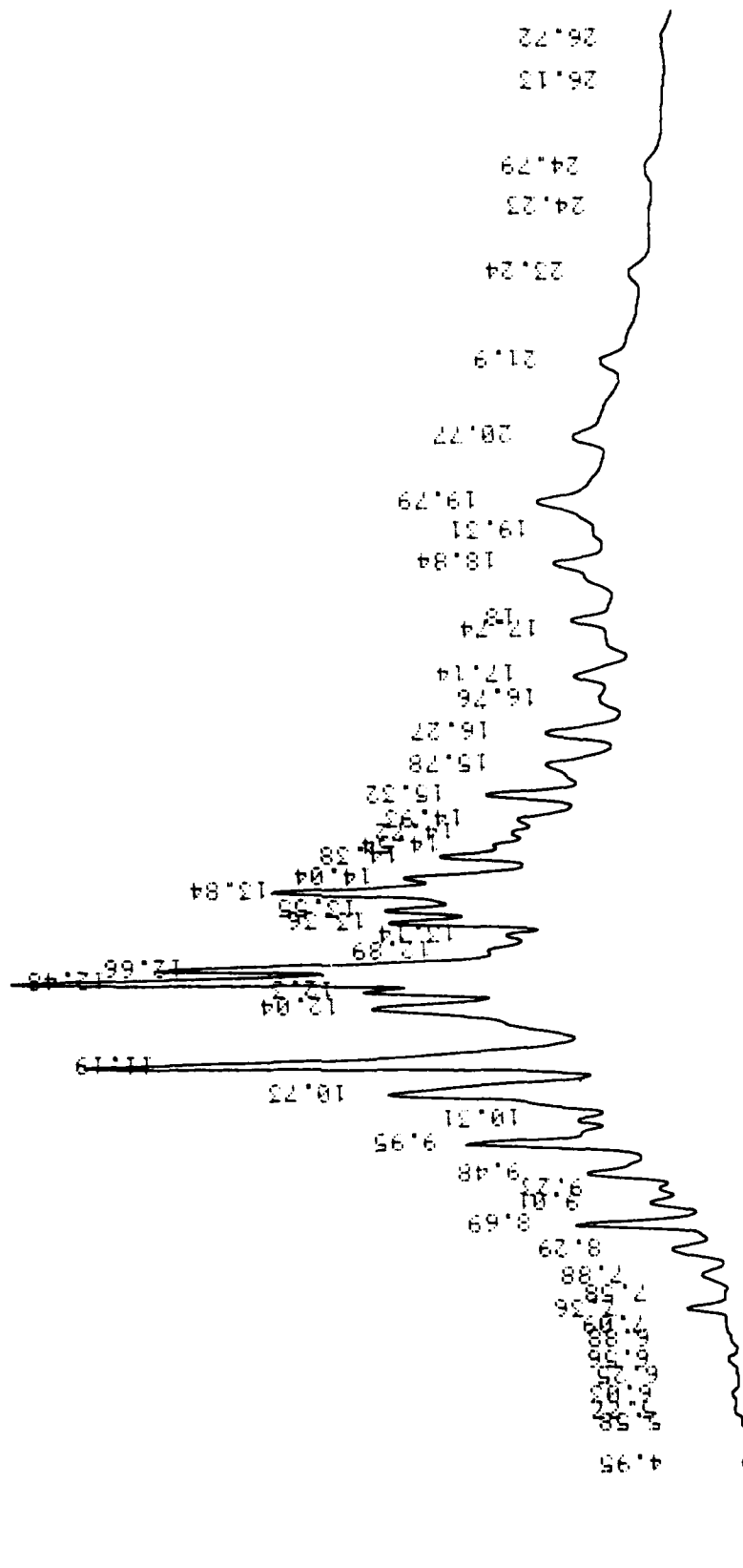


Figure 4.9 Gas chromatograph trace - No. 4 Fuel Oil--Fresh

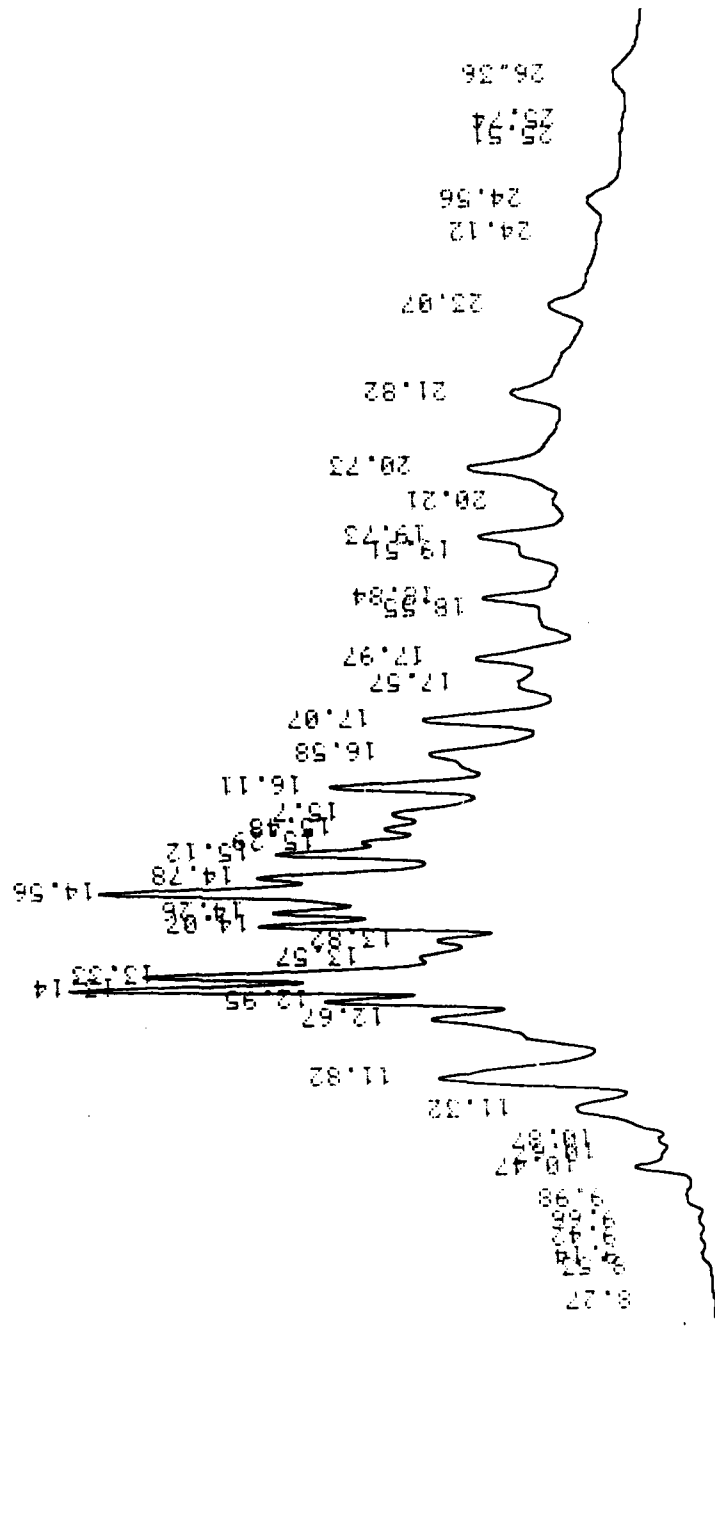


Figure 4.10 Gas chromatograph trace - No. 4 Fuel Oil--Weathered

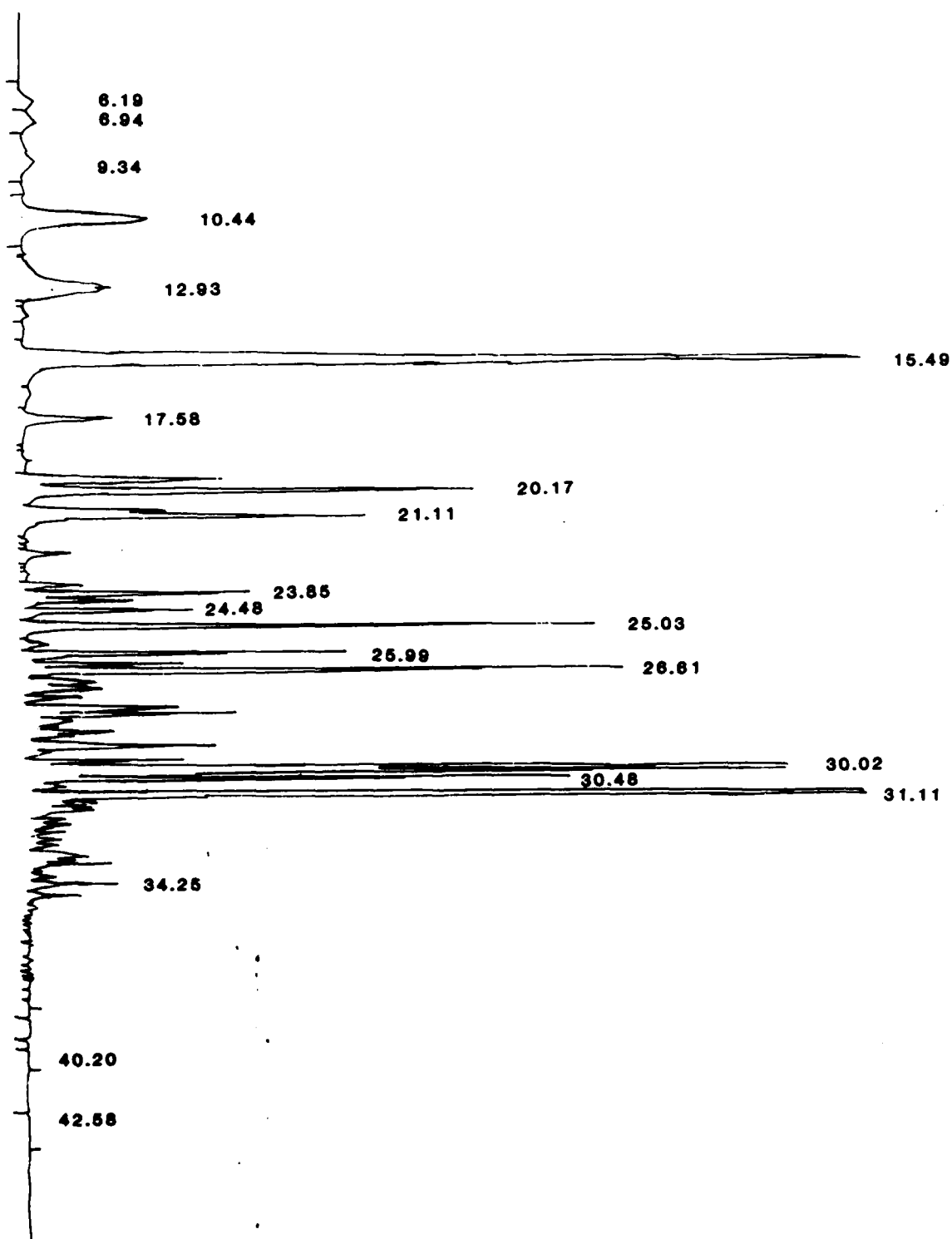


Figure 4.11 Gas chromatograph trace - Aqueous Solubility--Sample

Table 4.7. Emulsion Stability Test Results.

Test	OIL		
	P.B.C.	No. 2 H.H.	No. 4 F.O.
Mass fraction			
a) asphaltenes	0.024	0.0036	0.032
b) waxes	0.045	0.029	0.055
12 hour shaking test (1:3 oil-water ratio, 65 rpm)			
oil fraction emulsified	0.5	0.0	0.8 no water layer (2 phases only)
	forms fairly stable emulsion	forms no emulsion	forms stable emulsion

5.0 MODEL CALIBRATION AND DISCUSSION

Having obtained the analytical and property data for the oils and having developed the model for these oils, the final stage was to parameterize and run the model equations for the outdoor test conditions at Groton and predict the rates of oil evaporation and the resultant changes in oil properties. Comparison was then made against the actual properties measured experimentally. Because the outdoor conditions were not of constant windspeed and temperature, there is inevitably some loss of fidelity between model and experiment, and accommodation is possible by adjusting the rate constant for evaporation and the environmental conditions.

In practice, the full oil spill model was not used because spreading and dispersion did not occur. Some mousse formation did occur but it was believed to be due to rainfall and is not properly described by the model equations which apply to oceanic conditions. Accordingly, those sections of the model which apply to weathering and physical properties were removed and set up as a separate model.

From previous work, equations were proposed for the dependence of the properties on temperature and volume fraction evaporated (F), given in Table 5.1. These equations were then calibrated to the specific oil types by determining the equation constants, which are listed in Table 5.2. These constants were derived by fitting these equations to the experimental data on the samples obtained from the air-bubbling laboratory weathering procedures described in Section 4.1. The laboratory weathering data were used to derive the constants as this simulated weathering is caused exclusively by evaporation, which is the only process accounted for by the model equations. In the interests of simplicity, an attempt was made to fit the same constants (e.g., K_1 , K_2 , etc.) to all three oils, but this was not possible for viscosity and flash and fire points.

The first step in the calibration process is to relate the volume fraction evaporated (F) to the oil's degree of evaporation, i.e., the evaporative exposure.

The evaporation calculation is based on recent work by Stiver (1982) and Mackay and Stiver (1982) and is an extension of the evaporative exposure concept developed by Mackay and Paterson (1980).

The evaporation rate N (m^3/s) is given by

$$N = KAPv/RT$$

where K is a mass transfer coefficient (m/s), A is the oil area (m^2), P is the oil vapor pressure (atm), v is the oil liquid molar volume (m^3/mol), R is the gas constant ($82 \times 10^{-6} \text{ atm m}^3/\text{mol K}$) and T is absolute temperature (K). The dimensionless group (Pv/RT) is the oil's Henry's law constant, i.e., the ratio of the concentration in air (P/RT) to concentration in the oil (v), both in units of mol/m^3 . This group varies both with temperature and with extent or volume fraction of evaporation, F .

Table 5.1 Properties Measured and Correlated against F (volume fraction evaporated) and T (temperature K). A subscript 0 refers to conditions at 298 K ie. 25°C and F = 0, ie. fresh oil.

PROPERTY	UNITS	FUNCTION
Density	Kg/m^3	$\text{DEN} = \text{DEN}_0 (1 - K_1(T - T_0)) (1 + K_2F)$
Viscosity	mPas (cp)	$\text{VIS} = \text{VIS}_0 (\exp(K_3(1/T - 1/T_0)) \exp(K_4F))$
Aqueous Solubility	g/m^3	$\text{SOL} = \text{SOL}_0 \exp(-K_5F)$
Pour Point	°C	$\text{PP} = \text{PP}_0 (1 + K_6F)$
Flash Point	°C	$\text{FLP} = \text{FLP}_0 (1 + K_7F)$
Fire Point	°C	$\text{FIP} = \text{FIP}_0 (1 + K_8F)$
Oil Water Interfacial Tension	$\frac{\text{mN}}{\text{m}}$ (dyne/cm)	$\text{STW} = \text{STW}_0 (1 + K_9F)$
Oil-Air Interfacial Tension	$\frac{\text{mN}}{\text{m}}$ (dyne/cm)	$\text{STA} = \text{STA}_0 (1 + K_{10}F)$
Wax Content	mass fraction	$\text{WAX} = \text{WAX}_0 / (1 - F)$
Asphaltene Content	mass fraction	$\text{ASP} = \text{ASP}_0 / (1 - F)$

Table 5.2. Constants describing the Oil Properties as defined in Table 5.1.

Constant	PBC	HH	FO
K ₁	0.0008	0.0008	0.0008
K ₂	0.18	0.18	0.18
K ₃	9000	3000	7000
K ₄	10.5	1.6	5.0
K ₅	12.0	12.0	12.0
K ₆	0.35	0.35	0.35
K ₇	3.7	0.35	1.4
K ₈	3.7	0.35	1.4
K ₉	2.0	2.0	2.0
K ₁₀	1.0	1.0	1.0
DEN ₀	895	825	905
VIS ₀	35.0	4.0	23.0
SOL ₀	29.2	3.0	6.5
PP ₀	-2.0	-27.0	-3.0
FLP ₀	70.0	100.0	80.0
FIP ₀	80.0	110.0	90.0
STW ₀	27.0	26.0	30.0
STA ₀	30.0	26.0	32.0
WAX ₀	0.045	0.029	0.055
ASP ₀	0.024	0.0036	0.032

If the oil's initial volume is $V_0(\text{m}^3)$ then

$$N = V_0 dF/dt$$

hence $dF/dt = KAPv/V_0RT$

or $dF/d\theta = Pv/RT$ where $\theta = KAt/V_0$

θ is a dimensionless group termed the "evaporative exposure."

The problem is now to obtain an equation relating Pv/RT to F and temperature. The simplest procedure, which is suitable for fairly volatile oils, is to obtain the atmospheric pressure distillation equation of boiling point vs. F , namely,

$$T_B = A_n + B_n F \quad (A_n \text{ and } B_n \text{ are coefficients})$$

For several oils, the following relationship applies to give (Pv/RT) at 22°C :

$$\ln (Pv/RT) = 6.3 - 0.035 T_B$$

hence $\ln (Pv/RT) = 6.3 - 0.035A_n - 0.035 B_n F$

and substituting from above

$$\ln (dF/d\theta) = 6.3 - 0.035 A_n - 0.035 B_n F$$

Integrating this, and applying the initial condition that $\theta = 0$ at $F = 0$, gives

$$\theta = (\exp(0.035 B_n F) - 1)/(0.035 B_n \exp (6.3 - 0.035 A_n))$$

which gives an analytical relationship between θ and F , the evaporative exposure and mass fraction evaporated.

This approach was satisfactory for the Prudhoe Bay crude oil, but it failed for the distillates because of their high boiling points. Accordingly, separate constants were fitted for these oils, the 0.035 and 6.3 being changed. The final constants are given below.

Prudhoe Bay crude oil

$$\ln(Pv/RT) = 6.3 - 0.035T_B$$

$$T_B = A_1 + B_1 F \quad A_1 = 439 \quad B_1 = 804$$

Home Heating Oil

$$\ln(Pv/RT) = 50.1 - 0.12T_B$$

$$T_B = A_2 + B_2 F \quad A_2 = 521 \quad B_2 = 126$$

No. 4 Fuel Oil

$$\ln(Pv/RT) = 50.1 - 0.12T_B$$

$$T_B = A_3 + B_3 F \quad A_3 = 518 \quad B_3 = 239$$

It is hoped in future work to fit a single equation to cover the entire range of oils likely to be encountered environmentally.

For temperatures $T_E(K)$ other than $22^\circ C$ ($295^\circ K$), a correction is applied, namely

$$\ln(P_E/P_{22}) = 10.6 T_B(1/295 - 1/T_E)$$

Here T_E is the actual environmental temperature.

Now v also changes with temperature (as density ρ changes) as follows:

$$\rho_E = \rho_{22} (1 - K_1(T_E - 295))$$

therefore $v_E = v_{22}/(1 - K_1(T_E - 295))$

Combining these two corrections, and assuming that $\ln(RT)_E \approx \ln(RT)_{22}$ yields

$$\ln(Pv/RT)_E = \ln(Pv/RT)_{22} - \ln(1 - K_1(T_E - 295)) - 10.6 T_B(1/295 - 1/T_E)$$

The constant K_1 is given in Table 5.2.

In this manner, a set of calibrated equations was obtained for each oil type, which calculates the volume fraction evaporated (F) from the "evaporative exposure," and then calculates the oil physical properties as a function of F . The next step in the modelling effort was to compare the predicted values of F and the oil physical properties to the experimental data, to judge the accuracy of the model equations. A complete tabulation was prepared (which is not presented here, but is available at the R&D Center) of the individual experimental and calculated values for each oil sample. The summary results are presented in Figures 5.1 and 5.19 in the form of graphs of predicted versus experimental property values for volume fraction remaining, density, viscosity, solubility, pour point, flash point, fire point, and interfacial tensions. The data for each oil type are plotted separately.

The plots for volume fraction evaporated are given in Figures 5.1 to 5.3. The predicted values were obtained by first computing the evaporative exposure (θ), from the time duration, average wind speed, and average temperature values in Tables 4.1 to 4.3, and then using evaporative exposure to compute F according to the formulation outlined above. Experimental data, for the air-bubbled samples, were measured directly in the laboratory. However, such data were unavailable for the samples weathered under environmental conditions at the R&D Center due to inaccuracies in the measurement procedures. For these samples, volume fraction evaporated could only be estimated by inspecting the GC traces and matching with samples of known F . The estimated F values are given in Tables 4.4 to 4.6.

The comparisons between predicted and calculated oil physical properties are given in Figures 5.4 to 5.19. Predicted values were calculated according to the formulations set forth in Tables 5.1 and 5.2. Experimental values were obtained from the University of Toronto analysis, the results being summarized in Tables 4.4 to 4.6. For the density and viscosity plots, values for samples which were subject to emulsification have been identified, as these experimental values are not expected to agree with the values predicted by the evaporation model.

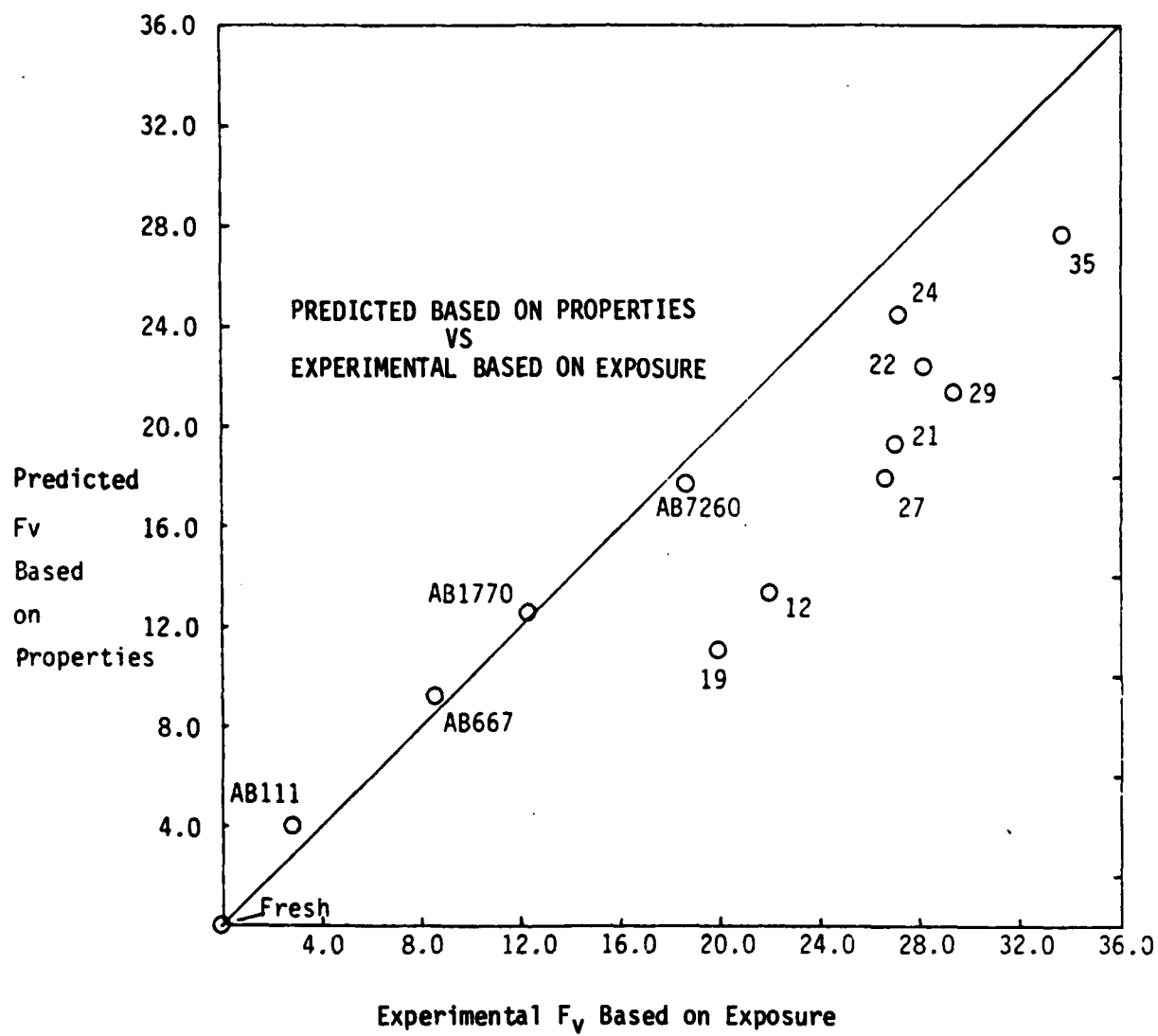


FIGURE 5.1 FRACTION EVAPORATED BY VOLUME--PRUDHOE BAY CRUDE

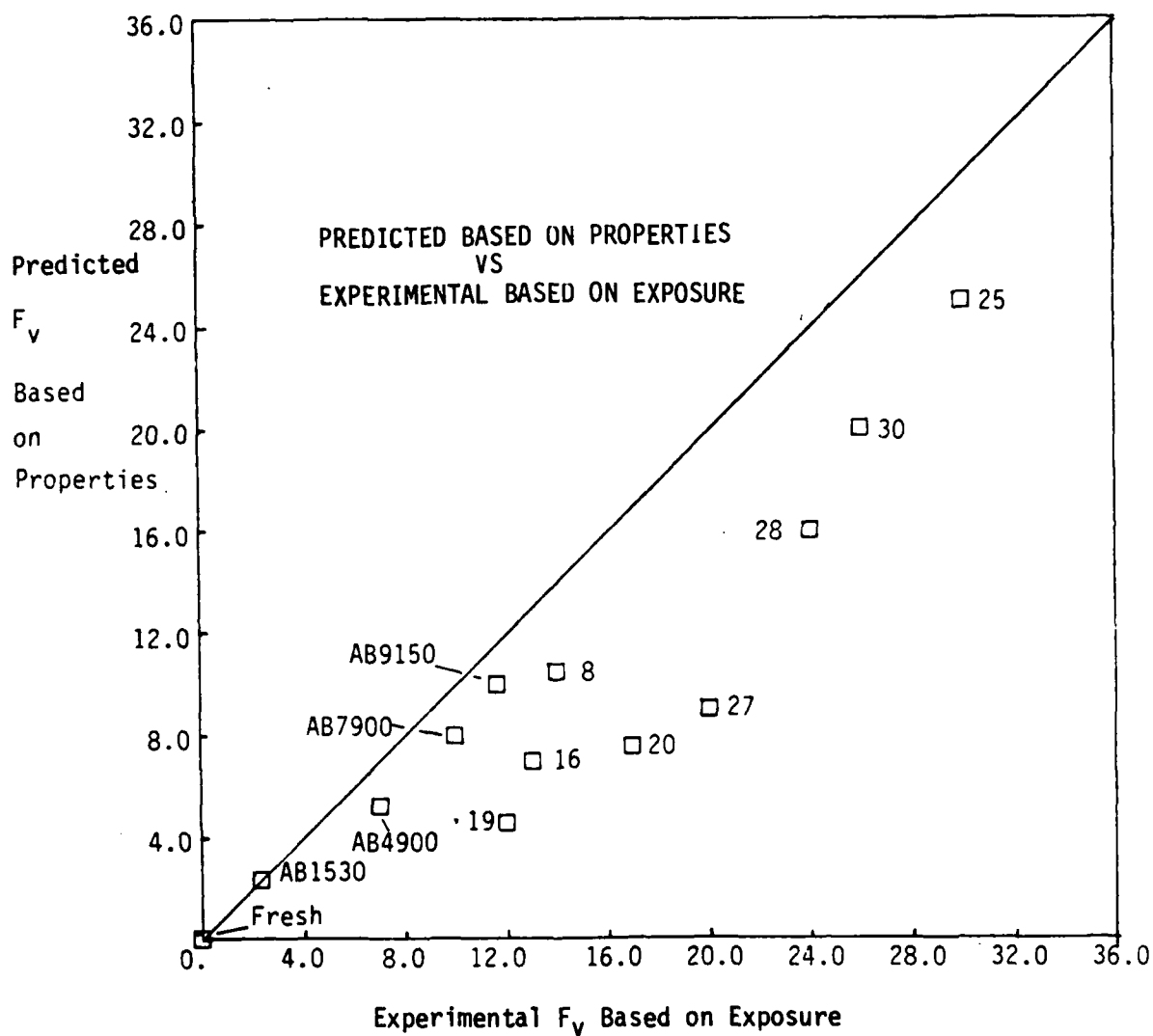


FIGURE 5.2 FRACTION EVAPORATED BY VOLUME--NO. 2 HOME HEATING OIL

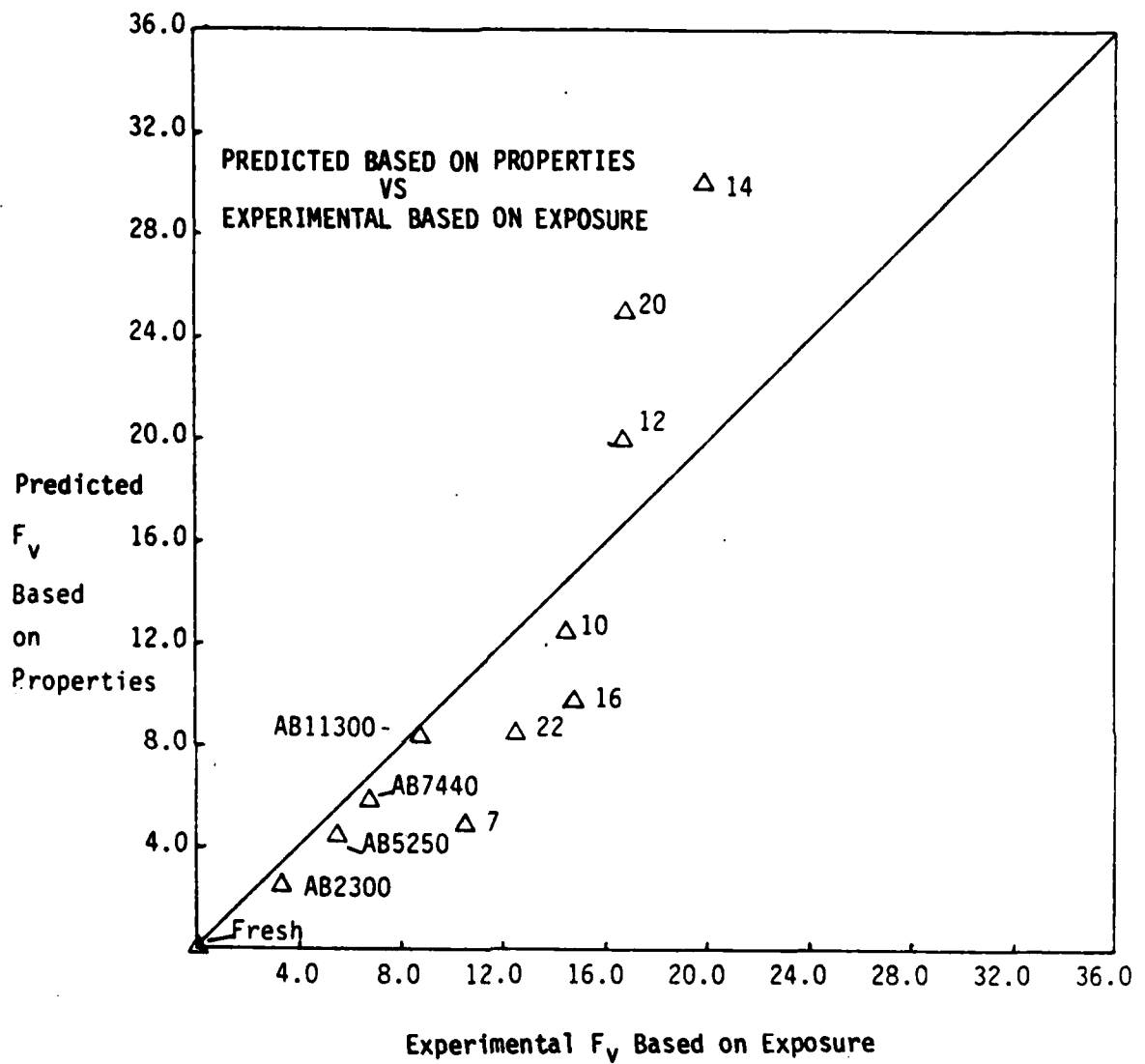


FIGURE 5.3 FRACTION EVAPORATED BY VOLUME--NO. 4 FUEL OIL

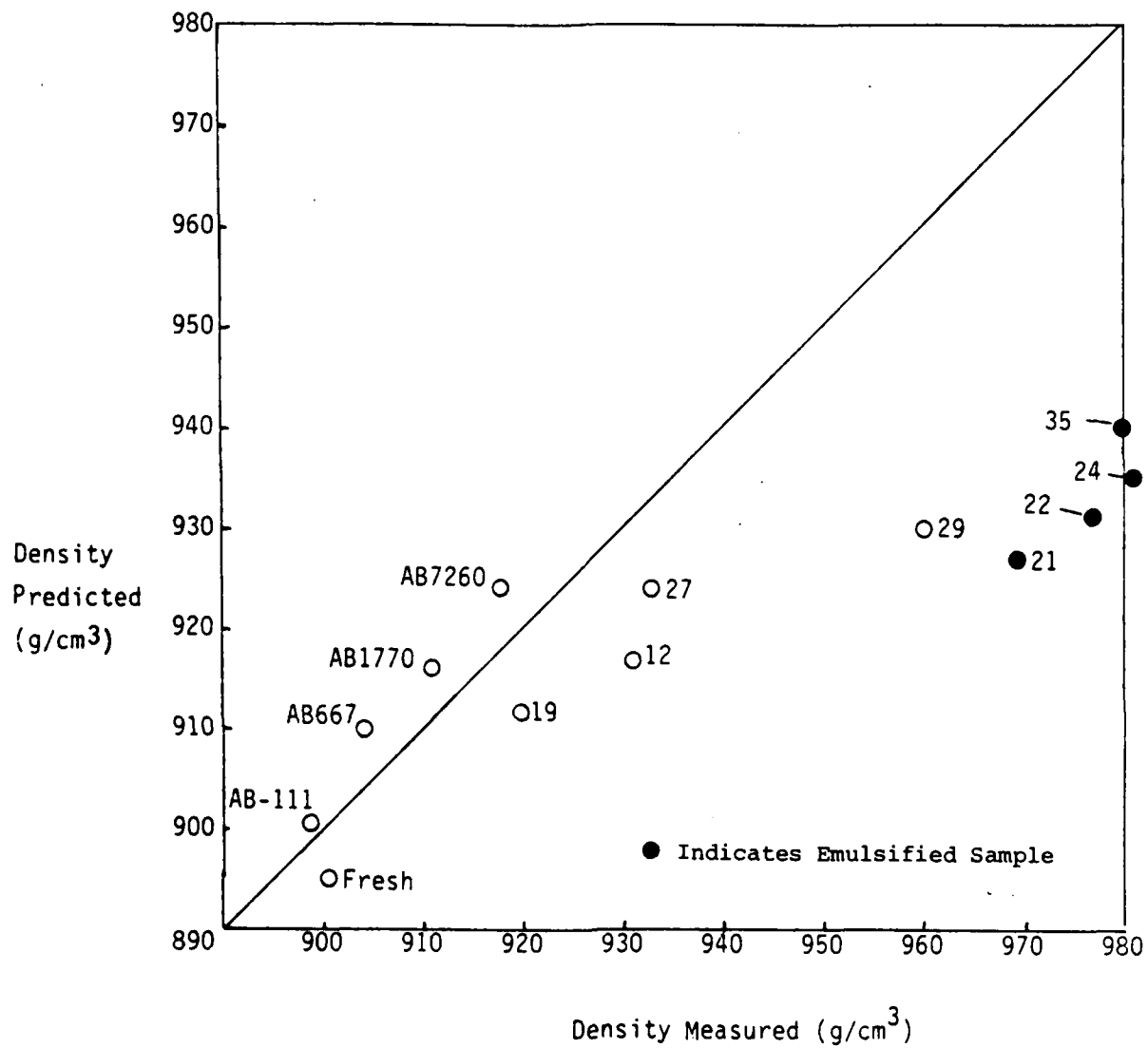


FIGURE 5.4 DENSITY--PRUDHOE BAY CRUDE

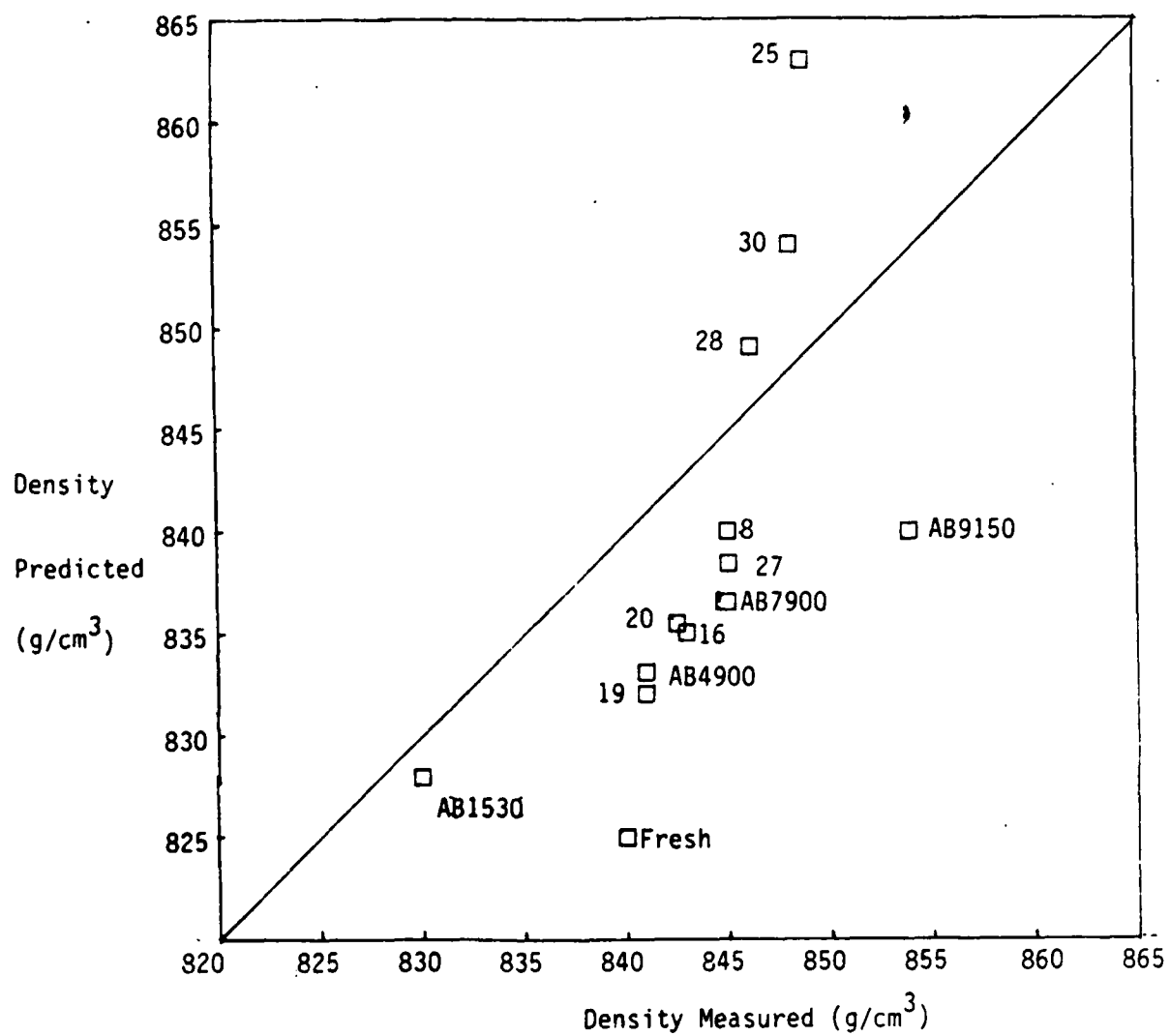


FIGURE 5.5 DENSITY--NO.2 HOME HEATING OIL

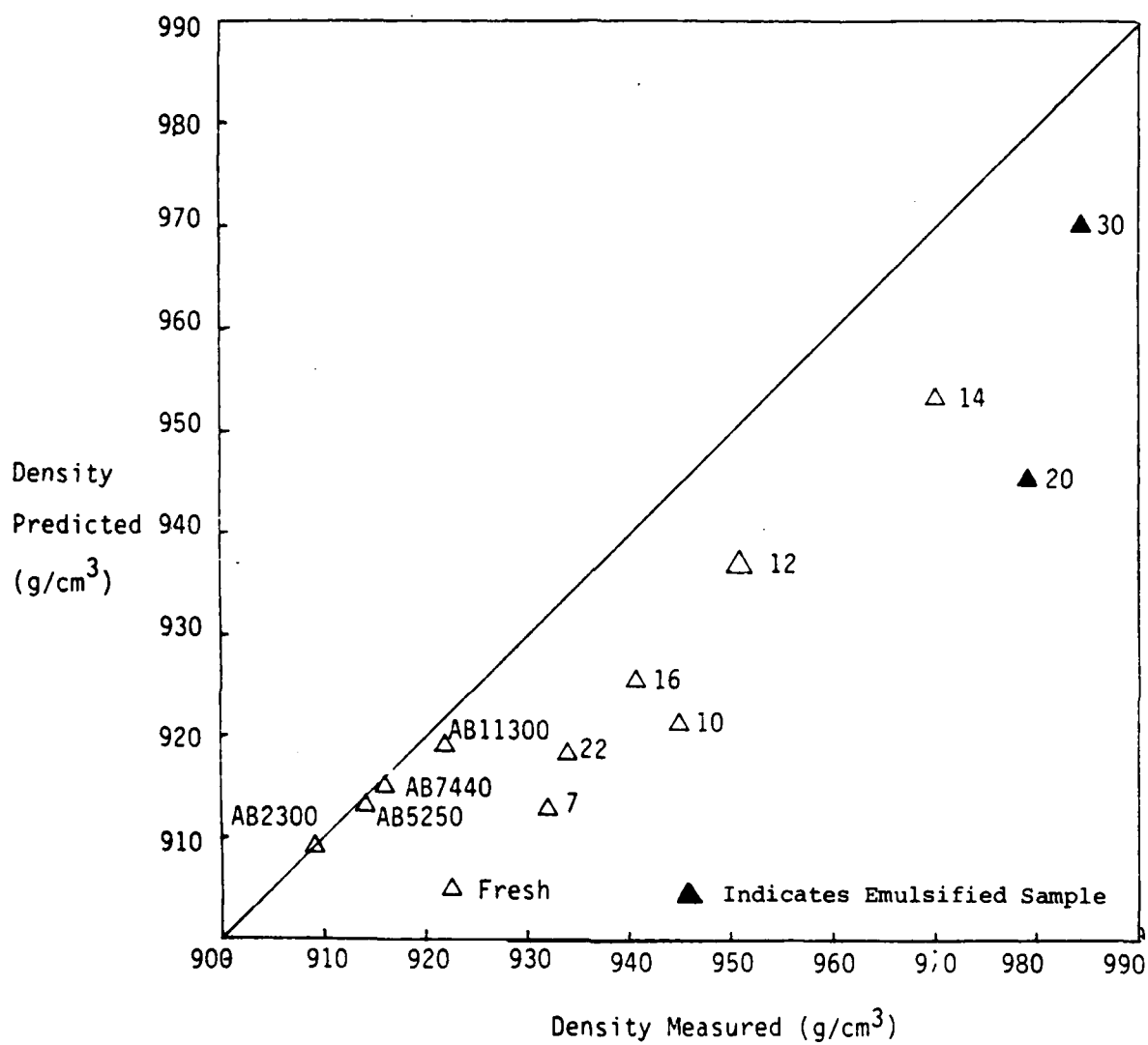


FIGURE 5.6 DENSITY--NO. 4 FUEL OIL

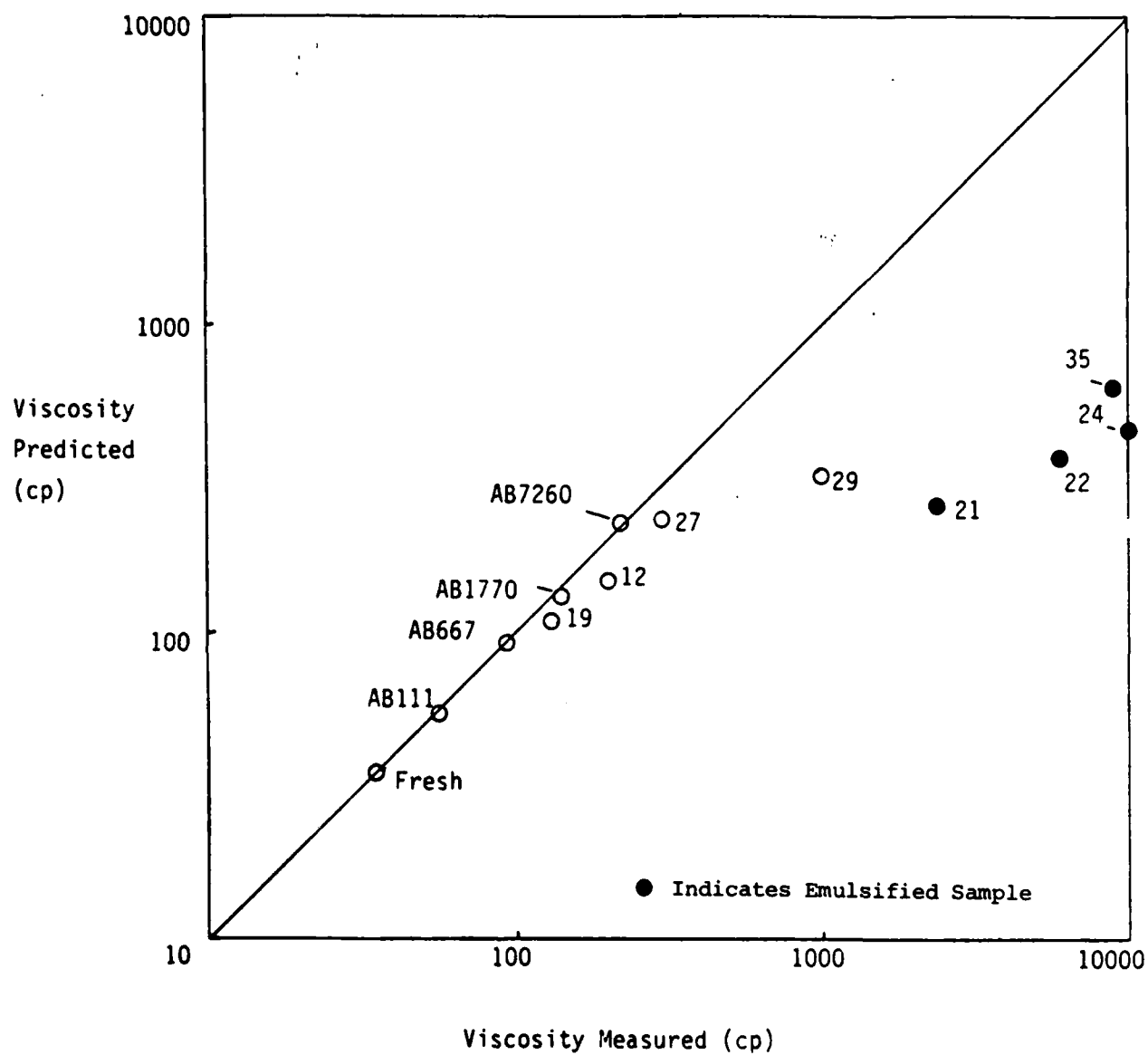


FIGURE 5.7 VISCOSITY--PRUDHOE BAY CRUDE

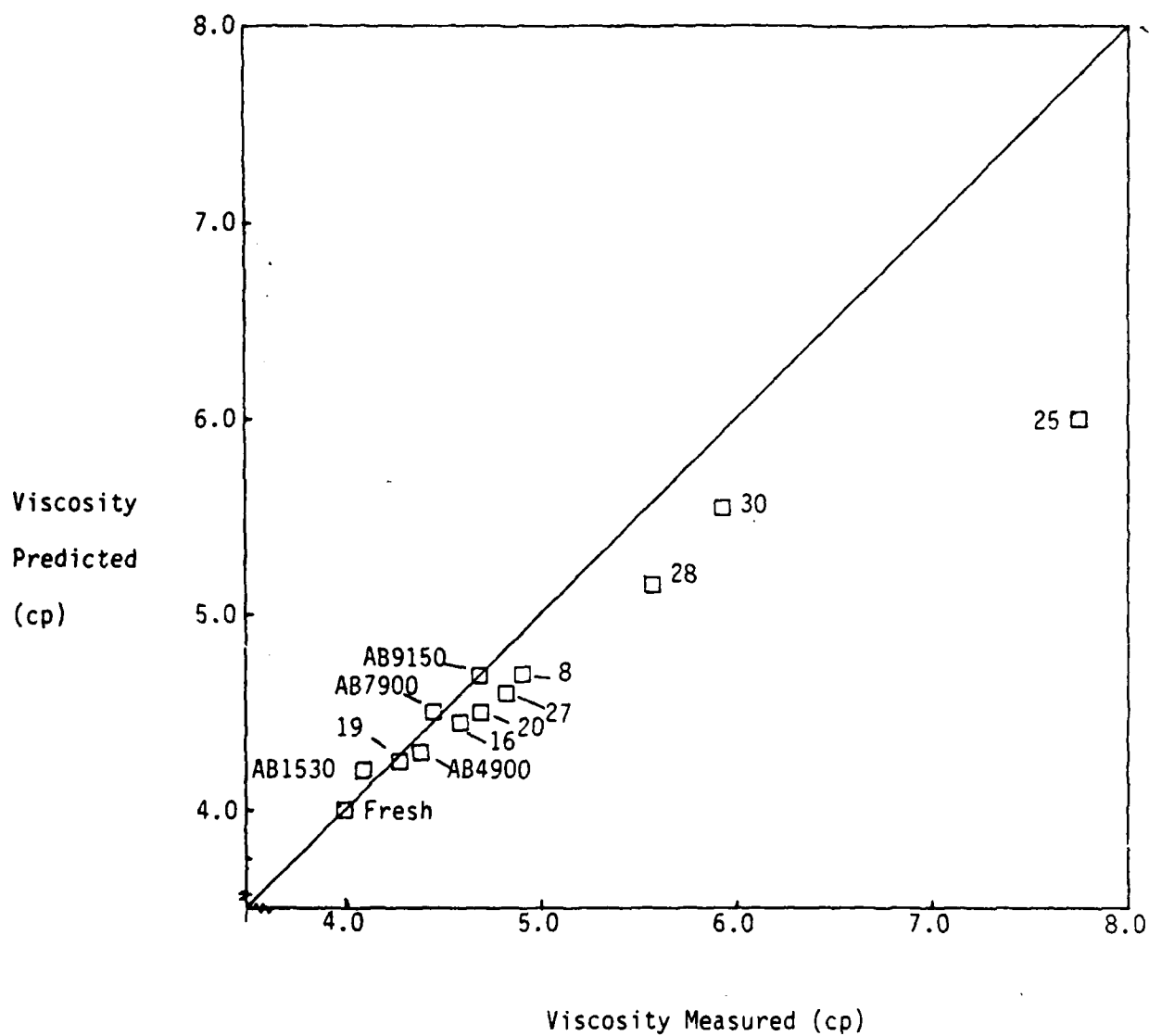


FIGURE 5.8 VISCOSITY--NO. 2 HOME HEATING OIL

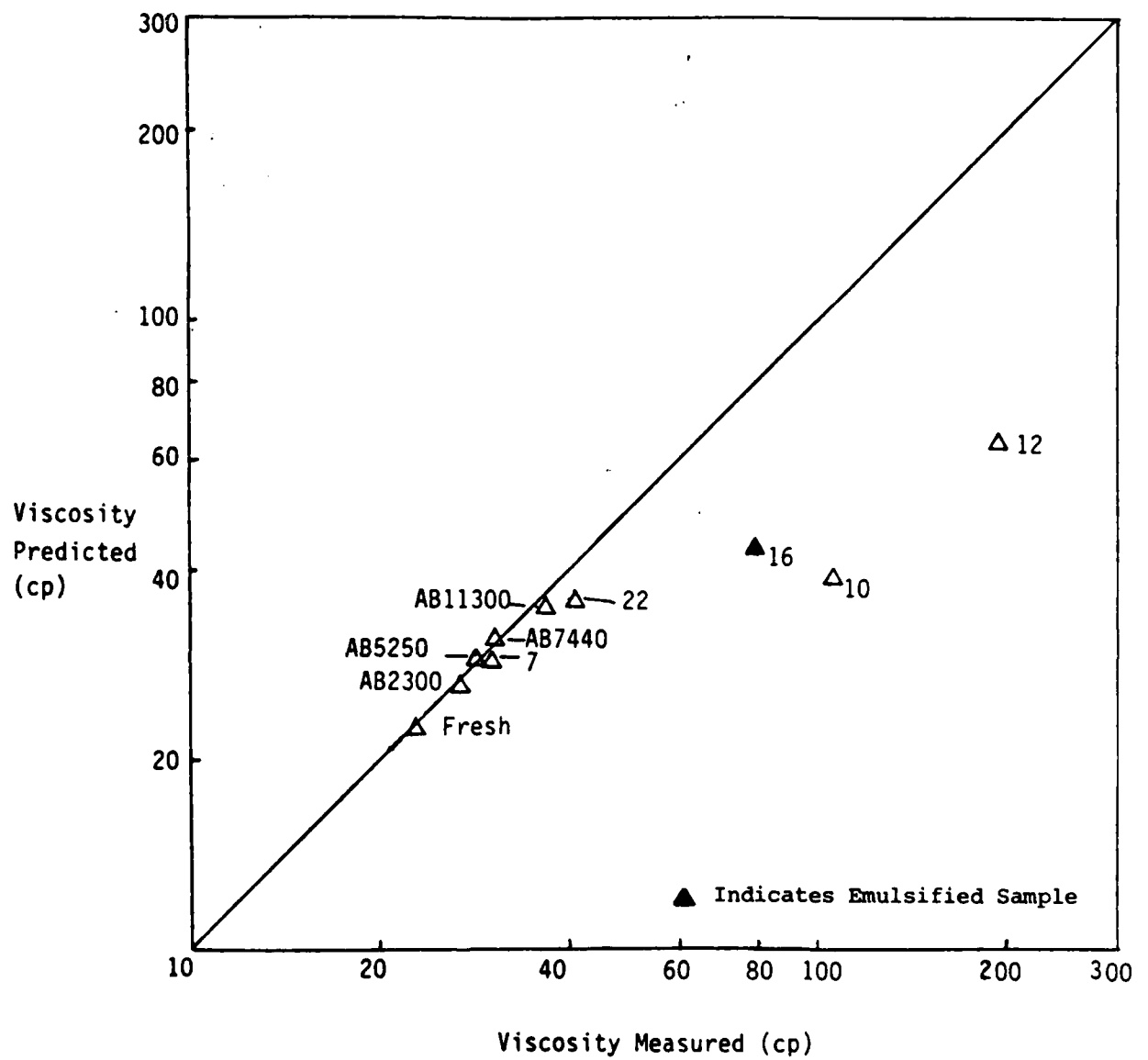


FIGURE 5.9 VISCOSITY--NO. 4 FUEL OIL

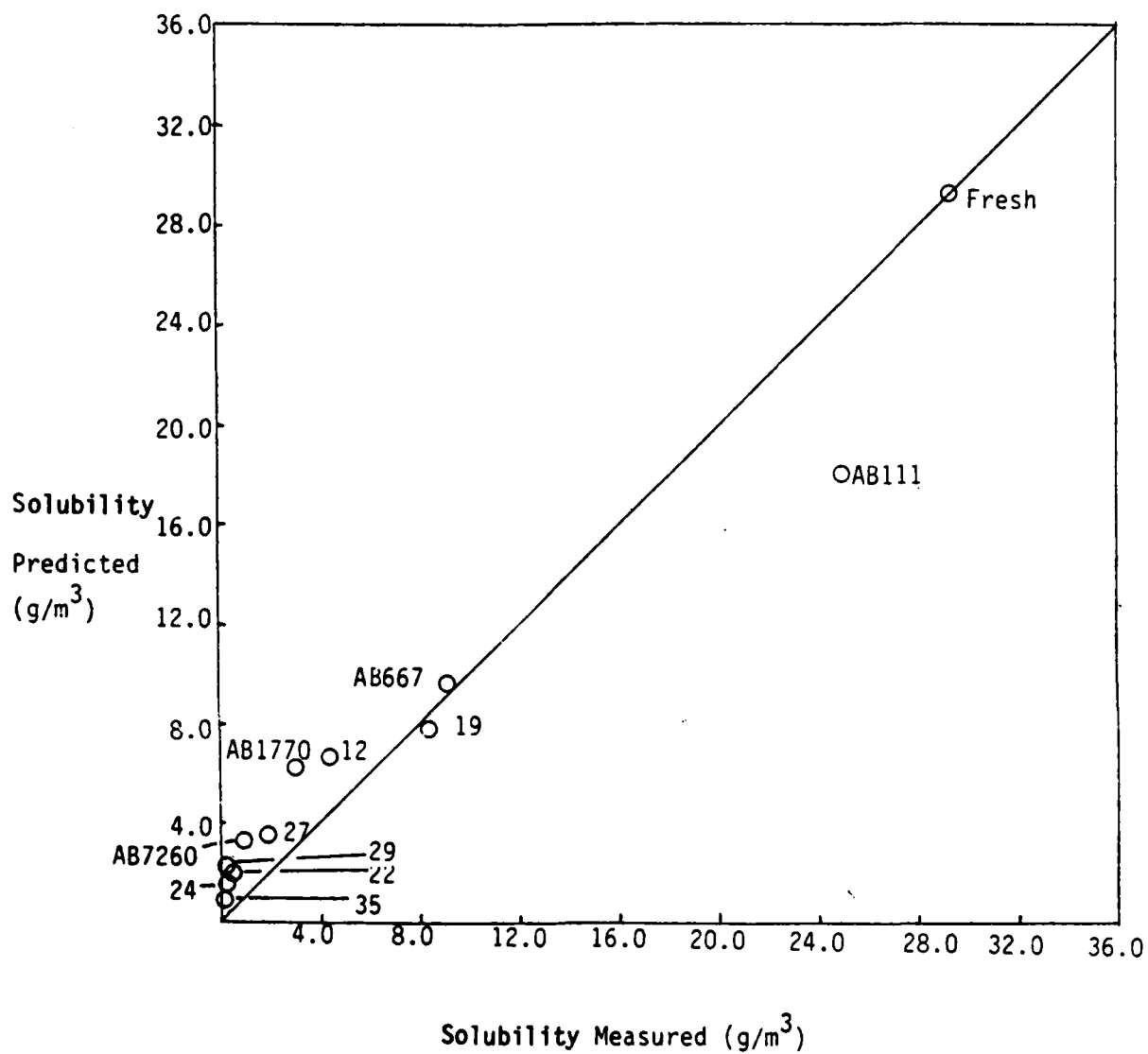


FIGURE 5.10 AQUEOUS SOLUBILITY--PRUDHOE BAY CRUDE

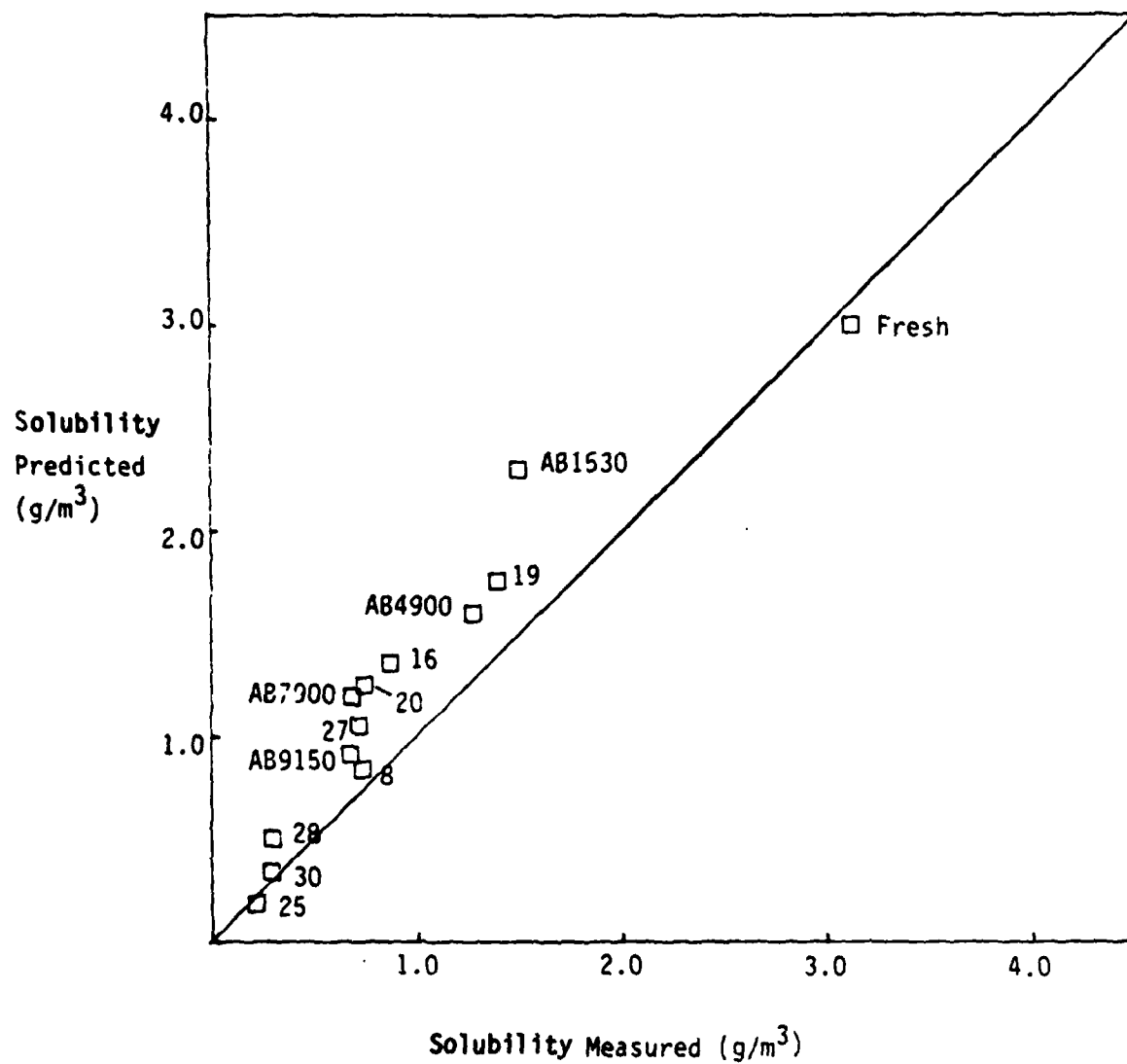


FIGURE 5.11 AQUEOUS SOLUBILITY--NO. 2 HOME HEATING OIL

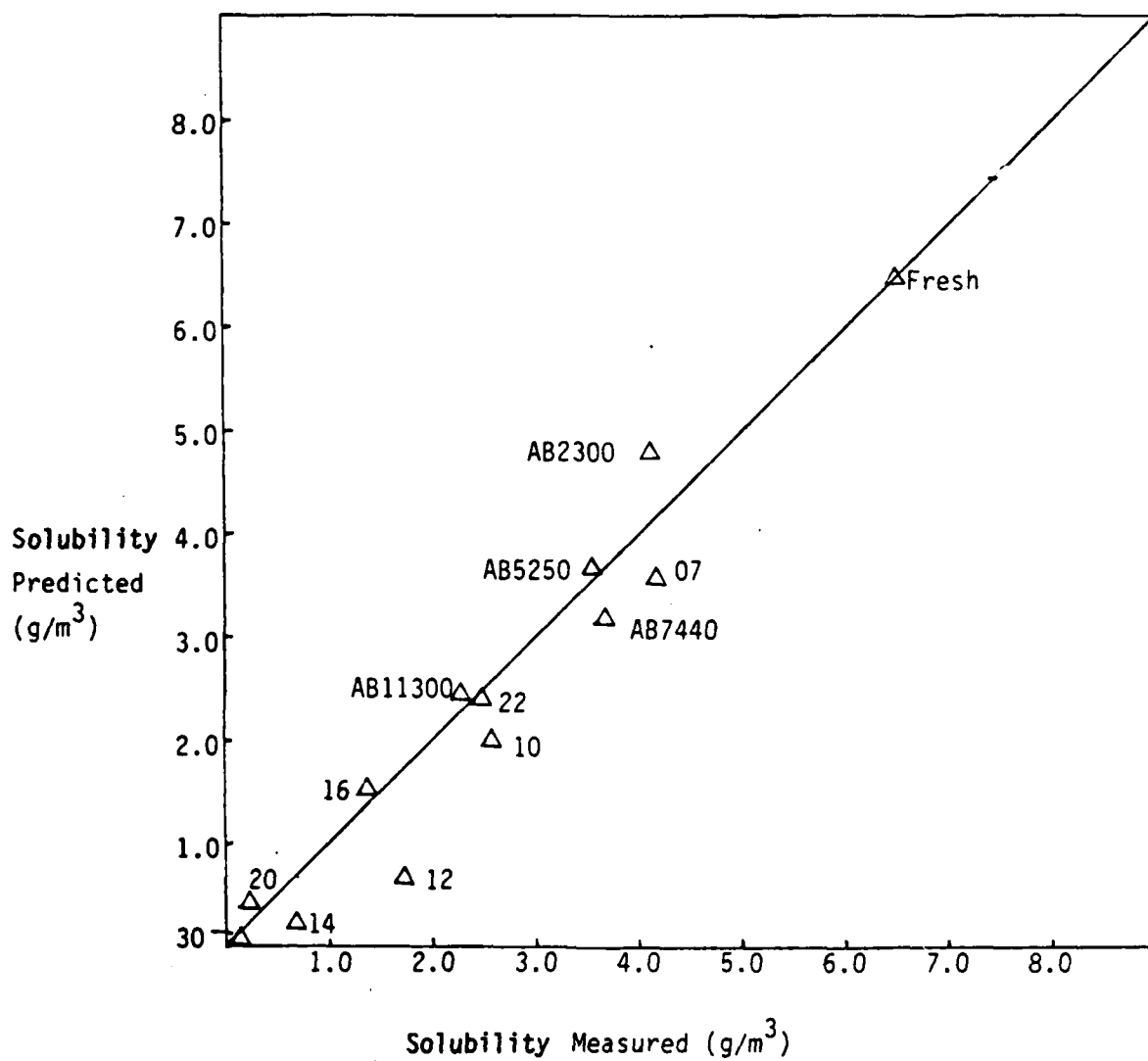


FIGURE 5.12 AQUEOUS SOLUBILITY--NO. 4 FUEL OIL

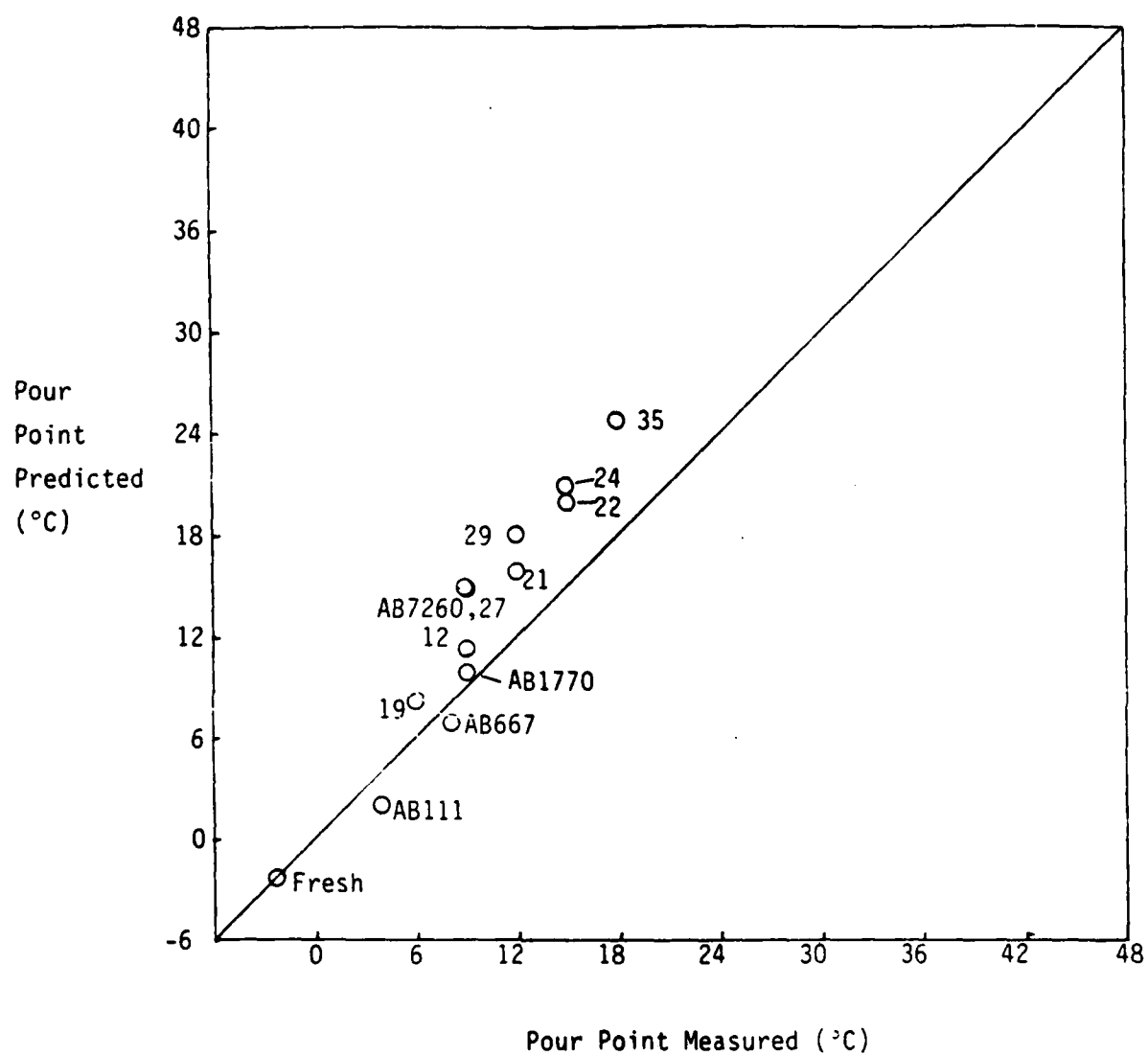


FIGURE 5.13 POUR POINT--PRUDHOE BAY CRUDE

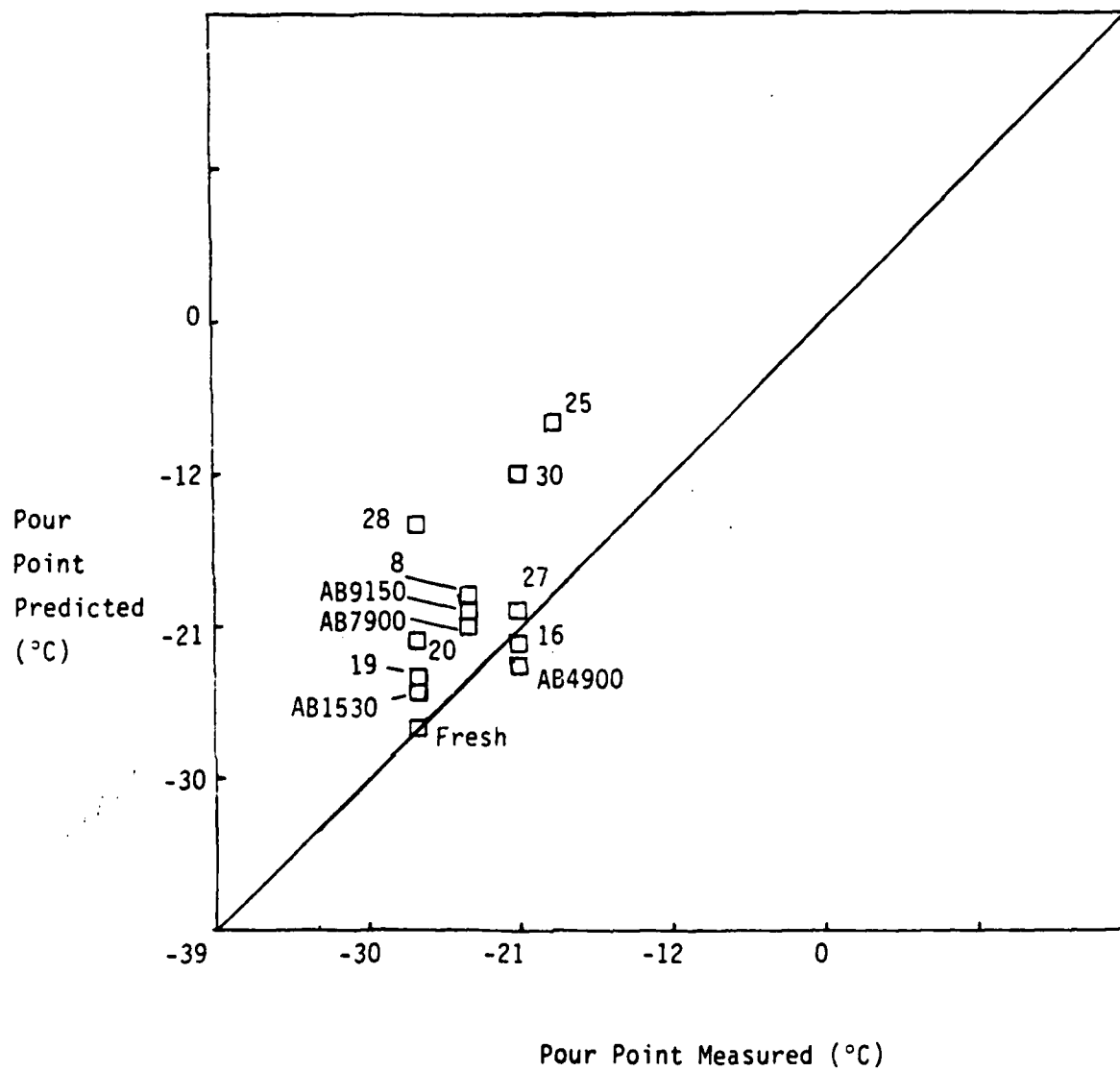


FIGURE 5.14 POUR POINT--NO. 2 HOME HEATING OIL

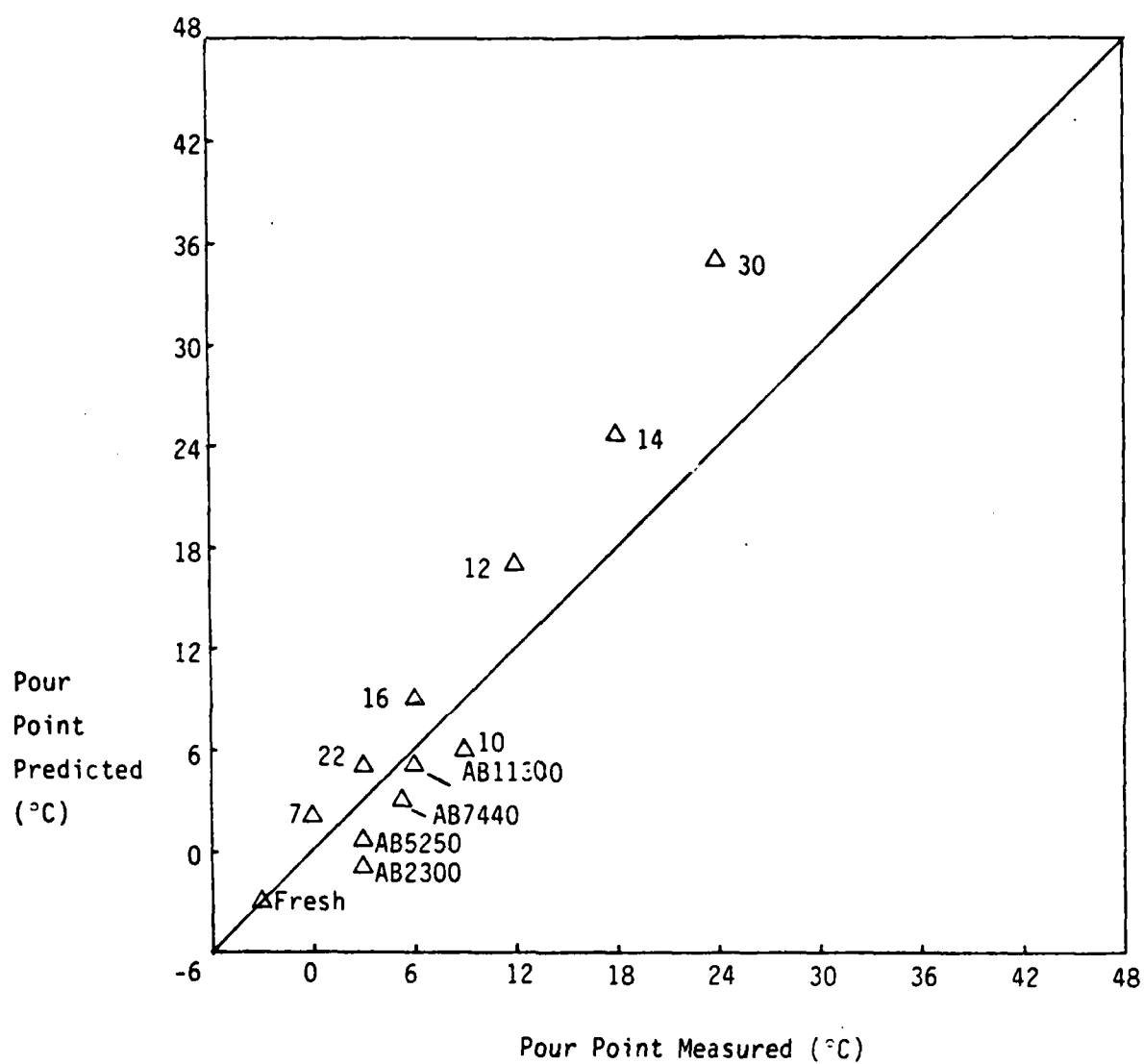


FIGURE 5.15 POUR POINT--NO. 4 FUEL OIL

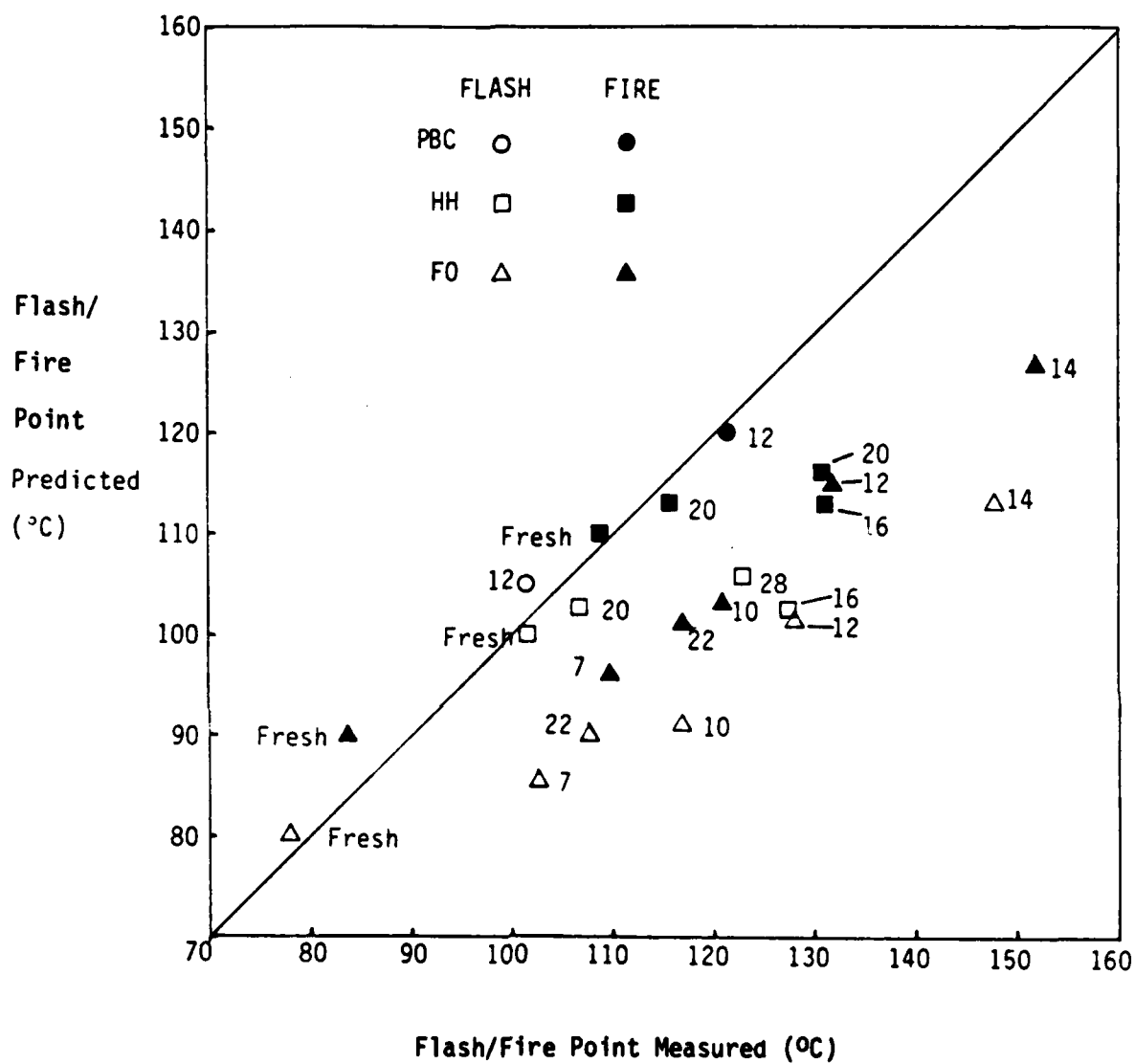


FIGURE 5.16 FLASH AND FIRE POINT

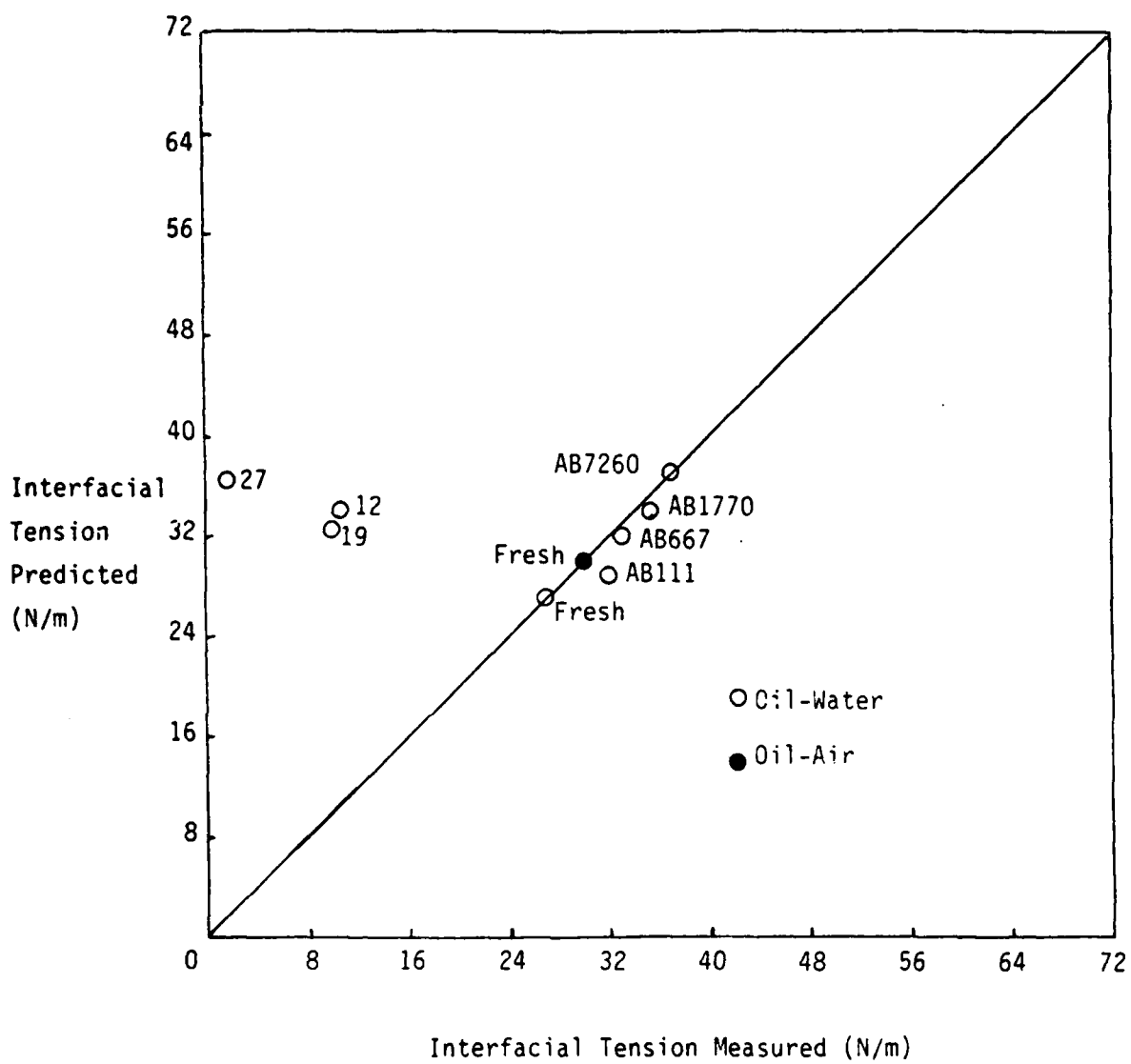


FIGURE 5.17 INTERFACIAL TENSION--PRUDHOE BAY CRUDE

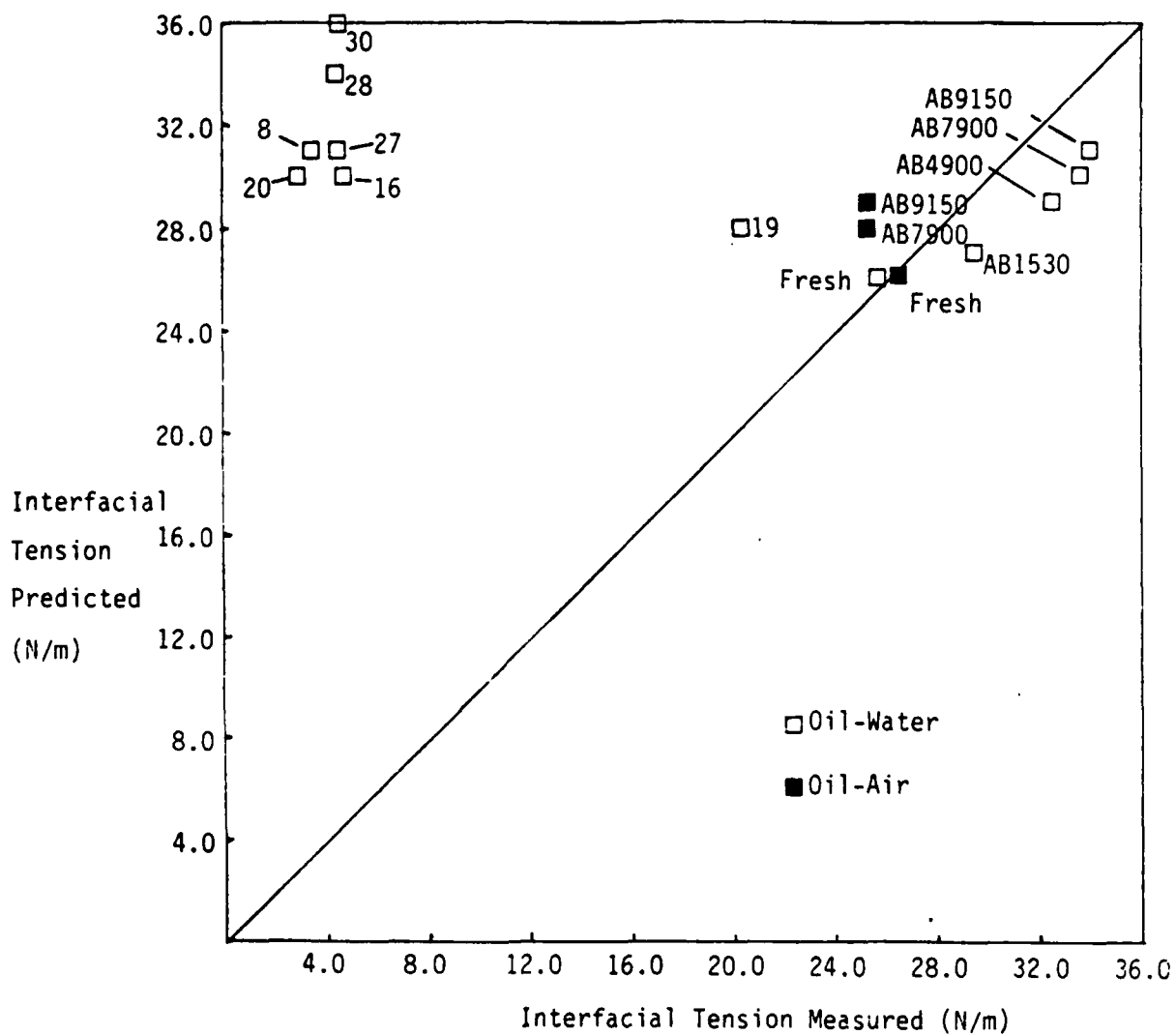


FIGURE 5.18 INTERFACIAL TENSION--NO. 2 HOME HEATING OIL

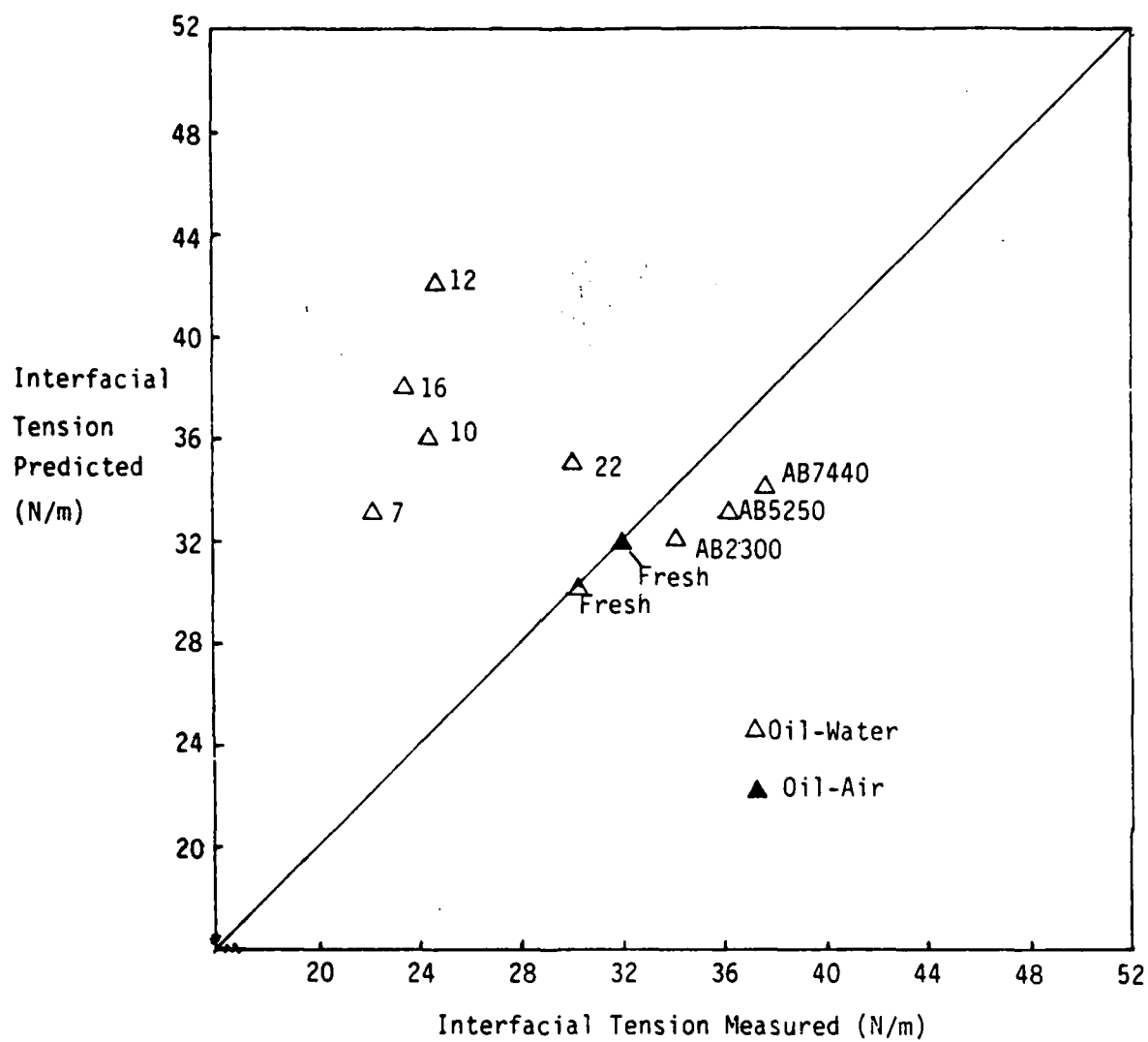


FIGURE 5.19 INTERFACIAL TENSION--NO. 4 FUEL OIL

The agreement between the predicted values and those measured as indicated in these figures was judged to be satisfactory in most cases. Prediction of the extent of evaporation is reasonably accurate considering the variability in environmental conditions and the uncertainty of the measured extent of evaporation. Density predictions were satisfactory with the exception of a few samples in which the discrepancy is attributed to formation of water-in-oil-emulsions which formed because the samples were exposed to rain. This phenomena is believed to cause the only major discrepancies in the viscosity predictions as well. Aqueous solubility, pour point, and flash and fire point estimation gave good results. Interfacial tensions were unpredictable. This is probably due to oxidation occurring in the environment which was not reproduced in the lab. Under the prolonged influence of sunlight and oxygen, it is likely that certain components of the oil (such as the asphaltenes) oxidize and form surface active compounds which reduce the interfacial tensions.

In general, the model provides a satisfactory predictive capability. The accuracy could be improved by selection of better equations and incorporation of more experimental data; but the significant advance in this work has been to establish for the first time the predictive framework and obtain reasonable parameter values.

6.0 CONCLUSIONS

An oil spill model has been developed, described, and provided to the Coast Guard R&D Center, Groton, CT. The model as originally developed includes calculation of rate of spreading, drift, evaporation, dispersion and water-in-oil emulsion formation. It also calculates the oil physical properties (density, viscosity, pour point, aqueous solubility, flash point, fire point, and interfacial tension) as a function of these weathering processes.

The focus of this study was to develop and calibrate a simplified version of this model which predicts volume fraction evaporated and physical properties based on evaporation alone for three types of oil under arctic conditions. The simplified evaporation model was calibrated using data obtained in simulated weathering (air-bubbling evaporation) experiments in the laboratory. The accuracy of the model was then judged by comparing the predicted values to experimental data obtained from outdoor weathering experiments at the R&D Center during the winters of 1979/80 and 1980/81. The results indicate that the model predicts oil density, viscosity, pour point, and aqueous solubility with a reasonable degree of accuracy. Attempts to predict flash and fire points, and interfacial tensions were not satisfactory. In view of this, the simplified model represents a significant contribution to predicting oil behavior and properties under arctic marine environmental conditions.

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APPENDIX A
OIL SPILL BEHAVIOR MODEL

INTRODUCTION

This Appendix gives a brief description of the model and instructions for input data. The program could be modified to become interactive by insertion of suitable statements.

The oil parameters used here are purely illustrative and do not reflect the properties of a given oil.

The input data are grouped into:

- (a) Computing parameters
- (b) Spill quantities
- (c) Environmental conditions
- (d) Oil properties
- (e) Process constants

(a) Computing Parameters

The following quantities must be defined:

DTIM - time increment (usually 100 s)

TCOMP - total time to be computed (e.g., 24 hours)

POFH - print out frequency in hours (e.g., every 0.1 hours)

(b) Spill Quantities

VOLTS - total volume spilled in m^3 (eg. 100)

TIMSP - duration of spill in seconds. This should be a multiple of DTIM. For an instantaneous spill set TIMSP to DTIM.

TTK - initial oil slick thickness (m) usually set at 0.02 m (2.0 cm)

TTN - thickness of sheen (m) usually 0.000005 m (5×10^{-6} m)

(c) Environmental Conditions

TC - temperature $^{\circ}C$ (eg. $15^{\circ}C$). Note that $^{\circ}F$ is printed out also.

WSKH - windspeed in km/h (eg. 20 km/h). Note that speeds in m/s and knots are also printed out.

FDR - oil drift factor (usually 0.035 or 3.5% of wind speed)

(d) Oil Properties

Note that all values must be inserted at 25°C. A correction is then made to the ambient temperature for density, viscosity and vapor pressure.

FMAX - maximum fraction evaporated (usually 0.4 but possibly lower)

ST - oil-water interfacial tension (usually 24 dynes/cm)

DEN25 - fresh oil density at 25°C (approximately 850 kg/m³)

VIS25 - fresh oil viscosity at 25°C (approximately 10 cPoise)

SOLO - fresh oil solubility (approximately 30 g/m³)

SENT, VIST - constants relating density and viscosity to temperature

DENK, VISK, SOLK - constants relating the change in density, viscosity and solubility to weathering. Typical values are 100, 4.0 and 12 respectively. The values of density viscosity and solubility (DENX, VISX, SOLX) at 10% weathering are calculated and printed out as a check.

(e) Process Constants

Evaporation

None are inputted but CE1, the evaporation mass transfer coefficient is calculated from wind speed. It is generally about 0.005 to 0.01 m/s. CE2 and CE3 are A and B respectively taken from the distillation curves for each oil (See Figure 4.4).

Dispersion

Three constants are inserted, CD1, CD2, and CD3 with values 0.00005, 2.0 and 1.0 respectively.

Emulsion Formation

Three constants are inserted, CM1 with value of 0.65, CM2 with value of 2×10^{-6} , and CM3 with value of 0.6 for PBC, 0.25 for HH, and 0.7 for FO.

Spreading

Four constants are inserted, CS1, CS2, CS3, and CS4 with values 1.0, 150, 5.0, and 8.0 respectively.

Note

In some cases, the values of these constants are oil dependent.

Shut-Off Factors

Five factors are read in with a value of 1.0 if the processes of evaporation, disperison, emulsion formation, spreading, and drifting are to proceed as normal. A value of zero stops the process and thus permits the impact of that process on overall spill behavior to be assessed.

COMPUTING PROCEDURE

- 1 - the program initializes a number of variables then proceeds to calculate the initial disposition of the slick and the oil properties.
- 2 - a print-out is then made of the spill conditions
- 3 - the oil spill behavior is then calculated as follows for the thick slick and the sheen
- 4 - time change is calculated
- 5 - evaporation amounts and rates are calculated
- 6 - dispersion amounts and rates are calculated
- 7 - emulsion formation amounts and viscosity are calculated
- 8 - spreading is calculated
- 9 - the new oil volumes, areas, composition and properties are calculated, any "new" spilled oil being added
- 10 - the slick position and shape is calculated
- 11 - the condition of the slick is then printed out if requested
- 12 - the program then returns to step 4, checking to determine if the program should stop.

```

*****
* BATHY THERM LEVS.          WARREN STIVER          MONITOR VERSION 3E *
* MONDAY AUGUST 9, 1982.          3:23 PM          *
*****

```

8-CHN 1C = WARREN STIVER

CIL SPILL MODEL PALOMAR BAY CRUDE

SET PARAMETER VALUES

```

SET COMPUTING CONDITIONS
TIME INCREMENT IN SECONDS - DTIM
CTIM=130.
TOTAL TIME COMPUTED IN HOURS - TCOMP
TCOMP = 25.0
NITT=TCOMP*3600/CTIM
PRINT OUT FREQUENCY IN HOURS
POPH = 4.0
ALPH=POPH*3600/CTIM
NIT=0.0
LOOP=NLP

```

```

SET SPILL CONDITIONS
TOTAL VOLUME SPILLED - VOLTS (M3)
VOLTS=100
DURATION OF SPILL IN SECONDS (MIN IS ONE INCREMENT) - TIMSP
TIMSP=100.0
TIMMP=TIMSP/3600.
TIM=0.0
CVCL=VOLTS/TIMSP
VIRVOL=DTIM
INITIAL THICK SLICK THICKNESS - TTK (M)
TTK=0.02
SHEEN THICKNESS - TTA (M)
TTA=0.000305
ZDL=0.0
ZOD=0.0
VRAT=0.0

```

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SET ENVIRONMENTAL CONDITIONS
TEMPERATURE - TC (DEGREES C)
TC = 2.
TK=TC+273.
TF=32.0+1.8*TC
WINDSPEED - WSKM (KM/HR)
WSKM=20
WSMS=WSKM/3.6
WSKN=WSMS*1.645
DRIFT FACTOR - FCR
FCR=0.035
VOR=FCR*WSMS
THETA = 0.

```

```

SET CIL PROPERTIES
MOLAR VOLUME - VMOL (M3/MOL)
MAX FRACTION EVAPORATED - FMAX
APR= 2.035 - 10.6*(1.0/295. - 1.0/TK)
BRP= 6.3 - ALG(1.0 - 0.0005*(TF-255.))
FMAX = 0.0
FTN=0.0
FTK=0.0
F=0.000082
CIL WATER INTERFACIAL TENSION - ST (DYNES/CM)
ST = 27.0
STN=ST
CIL DENSITY - DENO (KG/M3), WEATHERING CONSTANT - DENK
DEN25 = 810.
DENT= C.0-C6
DENC = DEN25 * (1 - DENT*(TC-25))
CIL VISCOSITY - VISO (CP/ISE), WEATHERING CONSTANT - VISK
VIS25 = 22.5
VIST= 5000.
VISK=10.5
VISO= VIS25 * EXP(VIST*(1.0/TK - 1.0/295.))
OIL SOLUBILITY - SOLC (G/M3), WEATHERING CONSTANT - SOLK
SOLC = 29.2
SOLK = 12.0
DENX = DENC * (1. + DENK * 0.1)
VISK = VISC * EXP (VISK*0.1)
SOLX = SOLC * EXP(- SOLK* 0.1)

```

```

EVAPORATION CONSTANTS
CE1=0.00047*(WSKM)*0.78
CE2 = 439.
CE3 = 804.
VTKE=0.0
VTNE=0.0
VTE=C.C

```

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DISPERSION CONSTANTS
CD1=0.0005
CD2=2.0
CD3=1.0
VTAO=0.0
VTAO=0.0
VTD=C.C

```

```

EMULSION CONSTANTS
CM1=0.05
CM2 = 2.0E-06
CM3 = 0.6
Fe=0.0
CF=0.0

```

```

SPREADING CONSTANTS
CS1=1.0
CS2=15.0
CS3=8.0
CS4=8.0

```



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133      TIMM=TIM/60.
134      TIMH=TIMM/60.
135      TIWD=TIMH/24.
136      C
137      C CALCULATE EVAPORATION (E)
138      THETA = THETA + CSI*ATK*CTIM*(1.-FTK)/VTK
139      FTK = ALG01EXP(ARR-ARR*CE2)*THETA *ARR*CE3 + 1.)/(ARR*CE3)
140      CVTKE = -(FTKE-FTK)* VTK/(1.-FTK)
141      DFTK = FTK - FTK
142      WKAT= THETA
143      DVTNE = - VTN*(FWAX -FTN)/(1.C-F1N)*EXP(-CTIM/500.)
144      VTKL=VTKL-CVTKE
145      VTNL=VTNL-CVTNE
146      VTE=VTKL+VTNL
147      PCTE=VTE*100.0/VSP
148      RATKE=-DVTKE/DTIM
149      RATNE=-DVTNE/DTIM
150      RATE=RATKE+RATNE
151      C
152      C DISPERSION (D)
153      IF (VISEM.GT.100.) THEN DO
154      RDK=0.0
155      ELSE DO
156      RDK=CD1*TTK*(WSMS/10.0)**2.0*EXP(-TTK*(CD2*STK/20.0+CD3*VISEM/
157      *100.0)/0.001)
158      END IF
159      RDN = CD1*TTN*(WSMS/10.0)**2.0*EXP(-TTN*(CD2*STK/20.0)/0.001)
160      RONT=RDN*ATN
161      RDKT=RDK*ATK
162      DVTKN=-RDKT*CTIM
163      CVTND=-RONT*DTIM
164      VTKD=VTKD-CVTKE
165      VTNL=VTNL-CVTNE
166      VTD=VTKD+VTND
167      FCTD=VTD*100.0/VSP
168      RATD=RONT+RDKT
169      C
170      C CALCULATE ACUSSE FORPATIC
171      VISE=EXP(2.5*FW/(1.-FW))
172      CF=CM2*(WSMS+1)**2.0*(1.-FW/CM3)*CTIM
173      FW=FW+CF
174      PCE=100.*FW
175      VISEM=VISE*VISE
176      C
177      C CALCULATE SPREADING (S)
178      DATNS=CSI*(ATN*0.33)*EXP(-CS3*TTN/TTK)*DTIM
179      DVTNS=DATNS*TTN
180      CVTKS=-DVTNS
181      DATKS = CS2*(100/VISEM)*(ATK*0.33)*(TTK-TTN)**1.33*DTIM-DVTNS/TTK
182      C
183      C CALCULATE NEW VOLUMES, AREA, ETC.
184      ATNC=ATN
185      ATKC=ATK
186      ATCC=ATC
187      VTK=VTK+DVTKE+DVTKD+DVTKE
188      VTN=VTN+DVTNE+CVTNE+CVTNS
189      ATN=VTN/TTN
190      ATK=ATK+DATKS
191      TTK=VTK/ATK
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227 WRITE(6,62C)PTA,PTK,FT
228 FORMAT(' ', 'FRACTION EVAPORATED', 25X, F10.6, 15X, F10.6, 15X, F12.8)
229 WRITE(6,63C) VTNE,VTKE,VTE,PCTE
230 FORMAT(' ', 'ANCLAT EVAPORATED', 27X, F10.6, 15X, F10.6, 15X, F10.6, 4X, F8
231 2.2//)
232 WRITE(6,61C)
233 612 FORMAT(' ', 'PROCESS RATES PER SECOND//')
234 WRITE(6,61C) CVOL
235 616 FORMAT(' ', 'CIL ADJUSTION', 57X, F12.8)
236 WRITE(6,61C) RAKT,RAKE,RATE
237 617 FORMAT(' ', 'EVAPORATION', 33X, F12.8, 13X, F12.8, 13X, F12.8)
238 WRITE(6,61C) ROKT,ROKT,RATC
239 618 FORMAT(' ', 'DISPERSION', 34X, F12.8, 2(13X, F12.8))
240 WRITE(6,61C) RATSX,RATSK,RATST
241 619 FORMAT(' ', 'SPREADING', 33X, F10.4, 2(15X, F10.4)//)
242 WRITE(6,324C)
243 324 FORMAT(' ', 'EVAPORATION DATA')
244 WRITE(6,32C) VRAT
245 325 FORMAT(' ', 'EVAPORATION AIR-OIL VOLUME RATIO', 18X, F12.3)
246 WRITE(6,32C) STK
247 326 FORMAT(' ', 'OIL-WATER INTERFACIAL TENSION', 24X, F5.2)
248 WRITE(6,487C) DEN, DENC
249 487 FORMAT(' ', 'THICK SLICK CIL DENSITY', 20X, F10.0, 6X, 'FRESH WAS', F10.
250 50)
251 WRITE(6,48C) SCL, SCLC
252 488 FORMAT(' ', 'THICK SLICK CIL SOLUBILITY', 21X, F10.4, 6X, 'FRESH WAS', F
253 610.4)
254 WRITE(6,48C) VIS, VISC, VISEX
255 486 FORMAT(' ', 'THICK SLICK OIL PARENT VISCOSITY', 15X, F10.4, 6X, 'FRESH
256 WAS', F10.4, 5X, 'EMULSION VISCOSITY IS', F10.4)
257 WRITE(6,62C) PCB, VISA
258 625 FORMAT(' ', 'WATER CONTENT OF THICK SLICK (VOL PERCENT)', 15X, F10.4,
259 510X, 'VISCOSITY RATIO', 10X, F10.4)
260 WRITE(6,63C) THKM
261 630 FORMAT(' ', 'THICKNESS OF THICK EMULSION SLICK', 18X, F12.8//)
262 WRITE(6,64C)
263 640 FORMAT(' ', 'SPILL LOCATION AND SHAPE//')
264 WRITE(6,64C) ZL, ZH
265 642 FORMAT(' ', 'LENGTH OF SPILL DOWNWIND', 12X, F12.0, 2X, 'M', 5X, 'WIDTH',
266 47X, F12.0, 2X, 'M')
267 WRITE(6,65C) ZLE, ZTE
268 650 FORMAT(' ', 'DISTANCE DOWNWIND', 15X, F12.0, 2X, 'M', 5X, 'LEADING EDGE',
269 F12.0, 2X, 'M', 5X, 'TRAILING EDGE//')
270
271 C
272 LOPF=-1
273 CONTINUE
274 LOPF=LOPF+1
275 VTK=VTA+DVCL*DTIM
276 VSPL=VSPL+CVCL*CTIM
277 TTK=VTK/ATK
278 PTK=PTK+DVCL*CTIM=PTK/VTK
279 S10 CONTINUE
280 RETURN
281 END

```

SCATA

A-8

THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
13619.34				425727.10		
0.036400				26.23		
0.000000				6.21600		0.22
0.008790				0.05597614		
2.761369				10.550780		10.85

THIN SLICK	242-22	W/ALTCES	100.00	10.00	100.00
412627.80					
0.000000					
0.000000					
0.210000					
0.394653					
1.754461					

THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
13619.34				425727.10		
0.036400				26.23		
0.000000				6.21600		0.22
0.008790				0.05597614		
2.761369				10.550780		10.85

THIN SLICK	242-22	W/ALTCES	100.00	10.00	100.00
412627.80					
0.000000					
0.000000					
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THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
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0.036400				26.23		
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412627.80					
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THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
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412627.80					
0.000000					
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THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
13619.34				425727.10		
0.036400				26.23		
0.000000				6.21600		0.22
0.008790				0.05597614		
2.761369				10.550780		10.85

THIN SLICK	242-22	W/ALTCES	100.00	10.00	100.00
412627.80					
0.000000					
0.000000					
0.210000					
0.394653					
1.754461					

THICK SLICK	4-06	4-CUPS	0-17	DAYS	TOTAL	PERCENT
13619.34				425727.10		
0.036400						

SPELL LOCATION AND SHAPE		BIDIM LEADING EDGE	726° N	TRAILING EDGE
LEAST OF SPILL DOWNING	726° N		726° N	
GISTACE DEBRIS	7207° N		2471° N	

[illegible][illegible]

REFILL LOCATION AND SHAPE	1127: A	PICM LEADING EDGE	1127: M	TRAILING EDGE
LENGTH OF SPILL DOWNWIND			1127: M	
EAST-WEST DISTANCE			1127: M	
DIRECTION OF WIND AT TIME OF SPILL			1127: M	
WIND SPEED			1127: M	
WIND DIRECTION			1127: M	
WIND VELOCITY			1127: M	
WIND PRESSURE			1127: M	
WIND TEMPERATURE			1127: M	
WIND HUMIDITY			1127: M	
WIND DENSITY			1127: M	
WIND VISCOSITY			1127: M	
WIND ACCELERATION			1127: M	
WIND DECELERATION			1127: M	
WIND JITTER			1127: M	
WIND FLUTTER			1127: M	
WIND SWAY			1127: M	
WIND ROCK			1127: M	
WIND ROLL			1127: M	
WIND YAW			1127: M	
WIND PITCH			1127: M	
WIND HEAVE			1127: M	
WIND SINK			1127: M	
WIND LIFT			1127: M	
WIND DRIFT			1127: M	
WIND SLIP			1127: M	
WIND GRAB			1127: M	
WIND HOLD			1127: M	
WIND RELEASE			1127: M	
WIND RETAIN			1127: M	
WIND REJECT			1127: M	
WIND ACCEPT			1127: M	
WIND REFUSE			1127: M	
WIND AGREE			1127: M	
WIND DISAGREE			1127: M	
WIND ASSESS			1127: M	
WIND EVALUATE			1127: M	
WIND ANALYZE			1127: M	
WIND SYNTHESIZE			1127: M	
WIND COMBINE			1127: M	
WIND SEPARATE			1127: M	
WIND INTEGRATE			1127: M	
WIND DIFFERENTIATE			1127: M	
WIND CLASSIFY			1127: M	
WIND UNCLASSIFY			1127: M	
WIND IDENTIFY			1127: M	
WIND MISIDENTIFY			1127: M	
WIND CONFIRM			1127: M	
WIND DENY			1127: M	
WIND SUSPECT			1127: M	
WIND PROVE			1127: M	
WIND DISPROVE			1127: M	
WIND VALIDATE			1127: M	
WIND INVALIDATE			1127: M	
WIND VERIFY			1127: M	
WIND UNVERIFY			1127: M	
WIND CHECK			1127: M	
WIND UNCHECK			1127: M	
WIND TEST			1127: M	
WIND UNTTEST			1127: M	
WIND MONITOR			1127: M	
WIND UNMONITOR			1127: M	
WIND OBSERVE			1127: M	
WIND UNOBSERVE			1127: M	
WIND PERFORM			1127: M	
WIND UNPERFORM			1127: M	
WIND EXECUTE			1127: M	
WIND UNEXECUTE			1127: M	
WIND IMPLEMENT			1127: M	
WIND UNIMPLEMENT			1127: M	
WIND ENFORCE			1127: M	
WIND UNENFORCE			1127: M	
WIND MAINTAIN			1127: M	
WIND UNMAINTAIN			1127: M	
WIND DEFEND			1127: M	
WIND UNDEFEND			1127: M	
WIND PROTECT			1127: M	
WIND UNPROTECT			1127: M	
WIND SECURE			1127: M	
WIND UNSECURE			1127: M	
WIND GUARANTEE			1127: M	
WIND UNGUARANTEE			1127: M	
WIND ASSURE			1127: M	
WIND UNASSURE			1127: M	
WIND SUPPORT			1127: M	
WIND UNSUPPORT			1127: M	
WIND BACKUP			1127: M	
WIND UNBACKUP			1127: M	
WIND RESTORE			1127: M	
WIND UNRESTORE			1127: M	
WIND RECOVER			1127: M	
WIND UNRECOVER				

VOLUME OF SPILL (CUBIC METRES)	100.00								
ITERATION NUMBER	436								
4360.00 SECONDS	720.67 MINUTES	12.11 HOURS	0.50 DAYS						
THIN SLICK		THICK SLICK	TOTAL	PERCENT					
1625194.00	12592.03	1641736.00							
AREA (SQUARE METRES)	814.72	70.10	78.25						
VOLUME (CUBIC METRES)	100.0000	0.003567	2.41002	2.41					
THICKNESS (METRES)	0.000005	0.000000	0.000000						
APPROXIMATE SPILLAGE (CUBIC METRES)	2790.75	0.000000	0.000000						
APPROXIMATE SPILLAGE (CUBIC METRES)	7.06160	12.27390	15.33550	19.34					
APPROXIMATE SPILLAGE (CUBIC METRES)									
PROCESS RATES PER SECOND									
OIL ACQUISITION	0.00000000	0.00000000	0.00027265						
EVAPORATION	0.00012367	0.00000000	0.00012367						
SPREADING	45.5660	-0.0709	45.5660						
EVAPORATION DATA									
EVAPORATION AIR-OIL VOLUME RATIO	2752.650								
EVAPORATION INTERFACIAL TENSION	27.00	FRESH WAS	906.						
THICK SLICK OIL SOLUBILITY	927.2984	FRESH WAS	25.2000						
THICK SLICK OIL PARENT VISCOSITY	1000.0040	FRESH WAS	261.3025						
WATER CONTENT OF THICK SLICK (VOL PERCENT)	55.2226	VISCOSITY RATIO	11.0049						
THICKNESS OF THICK EMULSION SLICK	0.01388								
SPILL LOCATION AND SHAPE									
LENGTH OF SPILL DOWNWIND	1446. M	WIDTH	1446. M						
DISTANCE DOWNWIND	9200. M	LEADING EDGE	7750. M						
		TRAILING EDGE							
VOLUME OF SPILL (CUBIC METRES)	100.00								
ITERATION NUMBER	1061								
50100.00 SECONDS	968.13 MINUTES	16.14 HOURS	0.67 DAYS						
THIN SLICK		THICK SLICK	TOTAL	PERCENT					
2292206.00	11395.01	2303601.00							
AREA (SQUARE METRES)	11.0000	60.72129	72.10						
VOLUME (CUBIC METRES)	100.0000	0.003000	4.57169	4.57					
THICKNESS (METRES)	0.000000	0.000000	0.000000						
APPROXIMATE SPILLAGE (CUBIC METRES)	4.57169	0.000000	0.000000						
APPROXIMATE SPILLAGE (CUBIC METRES)	0.000000	0.000000	0.000000						
APPROXIMATE SPILLAGE (CUBIC METRES)	10.17600	12.054800	22.23080	23.23					
PROCESS RATES PER SECOND									
OIL ACQUISITION	0.00000000	0.00000000	0.00026637						
EVAPORATION	0.00017415	0.00000000	0.00017415						
SPREADING	45.5660	-0.0914	45.5660						
EVAPORATION DATA									
EVAPORATION AIR-OIL VOLUME RATIO	58757.430								
EVAPORATION INTERFACIAL TENSION	27.00	FRESH WAS	906.						
THICK SLICK OIL SOLUBILITY	927.2984	FRESH WAS	25.2000						
THICK SLICK OIL PARENT VISCOSITY	1110.5750	FRESH WAS	261.3025						
WATER CONTENT OF THICK SLICK (VOL PERCENT)	55.2226	VISCOSITY RATIO	11.0049						
THICKNESS OF THICK EMULSION SLICK	0.01388								
SPILL LOCATION AND SHAPE									
LENGTH OF SPILL DOWNWIND	1713. M	WIDTH	1713. M						
DISTANCE DOWNWIND	12152. M	LEADING EDGE	10440. M						
		TRAILING EDGE							


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*****
* WATFIV VER1 LEV5.          MONITOR,VERSION 3E *
* MUNDAY AUGUST 9, 1982.    *ARREN STIVER      *
*****                                1:12 PM *

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0000 ID = 'ARREN STIVER'

CIL SPILL MODEL
AC. 2 NONE HEATING OIL

SET PARAMETER VALUES

SET COMPUTING CONDITIONS

TIME INCREMENT IN SECONDS - DTIM
CTIM=100.
TOTAL TIME COMPLETED IN HOURS - TCCMP
TCCMP = 25.0
NITT=TCCMP*3600/DTIM
PRINT OUT FREQUENCY IN HOURS
FOPH = 4.0
NLP=FOPH*3600/CTIM
NIT=0.0
LOCP=NLP

SET SPILL CONDITIONS

TOTAL VOLUME SPILLED - VCLTS (M3)
VCLTS=100
DURATION OF SPILL IN SECONDS (MIN IS ONE INCREMENT) - TIMSP
TIMSP=100.0
TIM=TIMSP/3600.
TIM=0.0
CVOL=VCLTS/TIMSP
VI=CVOL*DTIM
INITIAL THICK SLICK THICKNESS - TTK (M)
TTK=0.02
SHEEN THICKNESS - TTA (M)
TTA=0.0000000
ZOL=0.0
ZUD=0.0
VRAT=0.0

SET ENVIRONMENTAL CONDITIONS

TEMPERATURE - TC (DEGREES C)
TC = 2.
TK=TC+273.
TF=32.0+1.8*TC
WINDSPEED - WSKH (KM/HR)
WSKH=20
WSMS=WSKH/3.6
WSKN=WSMS*1.042
DRIFT FACTOR - FDR
FDR=0.015
VDR=FDR*WSMS
TPETA = 0.

SET CIL PROPERTIES

MOLAR VOLUME - VMOL (M3/MOL)
MAX FRACTION EVAPORATED - FMAX
FMAX = 0.12 - 10.6 * (1.0/295. - 1.0/TK)
BHP = 50.1 - ALOG(1.0 - 0.0002*(TK - 295.))
FMAX = 0.3
FTN=0.0
FTK=0.0
R=0.000082
CIL WATER INTERFACIAL TENSION - ST (DYNES/CM)
ST = 26.0
STK=ST
STN=ST
CIL DENSITY - DENC (KG/M3), WEATHERING CONSTANT - DENK
DENC = 820.
CENT = 0.0000000
DENO = DENC * (1 - CENT*(TC-25))
DENK = 0.16
CIL VISCOSITY - VISC (CPOISE), WEATHERING CONSTANT - VISK
VISC = 3.4
VIST = 3000.
VISK = 1.6
VISC = VIST * EXP(VIST*(1.0/TK - 1.0/295.))
CIL SOLUBILITY - SOLC (G/M3), WEATHERING CONSTANT - SOLK
SOLC = 3.0
SOLK = 12.0
DENS = DENC * (1. + DENK * 0.1)
VISC = VISC * EXP(VISK * 0.1)
SOLX = SOLC * EXP(- SOLK * 0.1)

EVAPORATION CONSTANTS

CE1=0.0000000*(WSKH)**0.78
CE2 = 521.
CE3 = 126.
VTR=0.0
VTNE=0.0
VTE=0.0

DISPERSION CONSTANTS

CD1=0.0000000
CD2=2.0
CD3=1.0
VTRC=0.0
VTND=0.0
VTD=0.0

EMULSION CONSTANTS

CM1=0.65
CM2 = 2.0E-06
CM3 = 0.25
Fb=0.0
DF=0.0

SPREADING CONSTANTS

CS1=1.0
CS2=150.
CS3=5.0
CS4=8.0

```

C VOLTS IS TOTAL VOLUME SPILLED (CUBIC METRES)
C VSPL IS VOLUME SPILLED TO GIVEN TIME (CUBIC METRES)
C TTM, TTM, TIME ARE TIME (SECONDS, MINUTES, HOURS, DAYS)
C DTIM IS TIME INCREMENT (SECONDS)
C TIMSP IS SPILL DURATION (SECONDS) (MUST EXCEED TIME)
C CVOL IS SPILL VOLUME INCREMENT
C PMAX IS MAXIMUM FRACTION OF THE OIL WHICH CAN EVAPORATE
C WSKH, WSKH AND WSKH ARE WIND SPEEDS IN KM/H, M/S AND KNOTS
C FOR IS WIND DIRECTION FACTOR
C TTN, TTK, TTK ARE THIN, THICK AND AVERAGE SPILL THICKNESSES
C ATN, ATK, ATD ARE THIN, THICK, AND TOTAL SPILL AREAS
C (SQUARE METRES)
C VTN, VTK, VTC ARE THIN, THICK AND TOTAL SPILL VOLUMES
C (CUBIC METRES)
C PTN, PTK AND PT ARE THIN, THICK AND TOTAL FRACTIONS EVAPORATED
C ST, STK AND STK ARE INITIAL, AND THIN AND THICK SLICK INTERFACIAL
C TENSIONS
C DENG, VISC AND SCLD ARE INITIAL DENSITY, VISCOSITY, AND SOLUBILITY
C OF THE OIL
C CEN, VIST, VPRY ARE CONSTANTS RELATING DENSITY, VISCOSITY AND
C VAPOR PRESSURE TO TEMPERATURE
C DEN25, VISC25, VPR25 ARE FRESH OIL DENSITY, VISCOSITY AND
C VAPOR PRESSURE AT 25 DEGREES C
C DENX, VISCX, SOLX, VPRX ARE VALUES OF DENSITY, VISCOSITY AND
C VAPOR PRESSURE AT 10X WEATHERING
C INITIAL RAT INDICATES RATES OF PROCESSES
C ZL, ZW ARE LENGTH AND WIDTH OF SLICK
C ZDL IS DRIFT LENGTH OF THE SPILL SOURCE POINT
C ZDD IS DRIFT LENGTH FROM LAST SPILL POINT
C TEXP IS EXPOSURE TIME (SECONDS)

C INITIAL D MEANS DELTA OR DIFFERENCE
C FINAL E INDICATES EVAPORATION
C FINAL C INDICATES DISPERSION
C FINAL M INDICATES EMULSIFICATION
C FINAL S INDICATES SPREADING
C FINAL W INDICATES DRIFT

C SHUT OFF FACTORS
71 SOFFD=1.0
72 SOFFD=1.0
73 SOFFW=1.0
74 SOFFS=1.0
75 SOFFW=1.0

C SHUT OFF PROCESSES
76 PMAX=MAX(COFFE
77 C1=SOFFD*CO1
78 CO1=SOFFD*CO1
79 CM2=SOFFW*CM2
80 CS1=CS1*SOFFS
81 CS2=CS2*SOFFS
82 FOR=FOR*SOFFW

C INITIAL CONDITIONS
C CALCULATION OF INITIAL DISPOSITION OF OILSLICK
83 VSPL=V1
84 ATK=V1/(TTN*CS4+TTN)

C
C
85 ATN=ATK*CS4
86 ATD=ATK*ATN
87 VTK=ATK*TTK
88 VTN=ATN*TTN

C CALCULATE INITIAL OIL PROPERTIES
C DENSITY
89 DEN = DENO*(1. + DENX*PTK)
C VISCOSITY
90 VIS = VISC * EXP(VISCX*PTK)
91 VISEN=VIS
C SOLUBILITY
92 SOL=SOL0*EXP(-SCLX*PTK)
93 WRITE(6,504) VCLTS
94 505 FORMAT('1', 'TOTAL VOLUME TO BE SPILLED=', F9.2, 2X, 'CUBIC METRES'///
1///)
95 WRITE(6,712) TIMSP, TIMHP
96 712 FORMAT('1', 'DURATION OF SPILL (S)', 12X, F9.1, 5X, 'OR', F11.3, 2X, 'H')
97 WRITE(6,713) V1
98 713 FORMAT('1', 'SPILL VOLUME INCREMENTS (M3)', 5X, F9.1)
99 WRITE(6,717) TTK, TTN, CS4
100 717 FORMAT('1', 'INITIAL SPILL THICKNESSES (M)', 5X, F11.6, 2X, 'THICK
*SLICK', 5X, F11.6, 2X, 'THIN SLICK', 5X, F11.6, 2X, 'AREA FACTOR'///)
101 WRITE(6,718)
102 718 FORMAT('0', 'ENVIRONMENTAL CONDITIONS'//)
103 WRITE(6,350) TC, TH
104 350 FORMAT('1', 'TEMPERATURE (DEGREES C)', 10X, F9.1, 5X, 'OR', F9.1, 2X,
*'(DEGREES F)'//)
105 WRITE(6,351) WSKH, WSKH, WSKH
106 351 FORMAT('1', 'WIND SPEED (KM/H)', 12X, F9.1, 5X, 'OR', F9.1, 2X, 'M/S', 5X,
*'(OR', F9.1, 1X, 'KNOTS'//)
107 WRITE(6,710) FCR
108 710 FORMAT('1', 'DRIFT FACTOR', 24X, F6.3//)
109 WRITE(6,700)
110 700 FORMAT('0', 'OIL PROPERTIES'//)
111 WRITE(6,701)
112 701 FORMAT('0', 23X, 'INITIAL VALUE', 12X, 'WEATHERING CONSTANT', 6X,
*VALUE AT 10 PERCENT', 5X, 'INITIAL VALUE', /68X, 'EVAPORATION', 12X,
*AT 25 C'//)
113 WRITE(6,722) DENG, DENX, DENX, DENX
114 722 FORMAT('1', 'DENSITY (KG/M3)', 16X, F15.6, 3(10X, F15.6))
115 WRITE(6,711) VISC, VISCX, VISCX, VISCX
116 711 FORMAT('1', 'VISCOSITY (MPAS)', 14X, F15.6, 3(10X, F15.6))
117 WRITE(6,723) SCLD, SCLX, SCLX
118 723 FORMAT('1', 'SOLUBILITY (G/M3)', 12X, F15.6, 2(10X, F15.6))
119 WRITE(6,704)
120 704 FORMAT('1', 'VAPOR PRESSURES ARE NOT CALCULATED INDEPENDENTLY'///)
121 WRITE(6,705)
122 705 FORMAT('0', 'PROCESS CONSTANTS'//)
123 WRITE(6,706) CO1
124 706 FORMAT('1', 'EVAPORATION', 21X, F15.8)
125 WRITE(6,727) CO1, CO2, CO3
126 727 FORMAT('1', 'DISPERSION', 22X, F15.8, 2(10X, F15.8))
127 WRITE(6,708) CM1, CM2, CM3
128 708 FORMAT('1', 'EMULSIFICATION', 18X, F15.8, 2(10X, F15.8))
129 WRITE(6,709) CS1, CS2, CS3
130 709 FORMAT('1', 'SPREADING', 22X, F15.8, 2(10X, F15.8))
C
131 DO 510 L=1, NIT
132 TIME=TIME+DTIM

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133 TIMM=TIM/60.
134 TIMH=TIMM/60.
135 TIMD=TIMM/24.
C
136 CALCULATE EVAPORATION (E)
137 THETA = THETA + CEL*ATK*CTIM*(1.-FTK)/VTK
138 FTK = ALG(CAR(DIP-ARP*CE2)*THETA +ARP*CE3 + 1.)/(ARP*CE3)
139 CVTKE = -(FTK-FTK)*VTK/(1.-FTK)
140 CFK = FTK - FTK
141 VRAT = THETA
142 DVTNE = -VTN*(FMAX -FTN)/(1.0-FTN)*EXP(-CTIM/500.)
143 VTK=VTK-CVTKE
144 VTNE=VTNE-CVTNE
145 VTE=VTK+VTNE
146 PCTE=VTE*100./VSPL
147 RATKE=-DVTKE/CTIM
148 RATNE=-DVTNE/CTIM
149 RATE=RATKE+RATNE
C
149 DISPERSION (D)
150 IF (VISEM.GT.1000.) THEN DO
151 RDK=0.0
152 ELSE DO
153 RDK=CD1*TTK*(WSMS/10.0)**2.0*EXP(-TTK*(CE2*STK/20.0+CD3*VISEM/
154 *100.0)/0.001)
155 END IF
156 RDN = CD1*TTN*(WSMS/10.0)**2.0*EXP(-TTN*(CE2*STK/20.0)/0.001)
157 RDN=RDN*ATN
158 RDKT=RDK*ATK
159 DVTKD=-RDKT*CTIM
160 CVTND=-RDN*CTIM
161 VTKD=VTK-CVTKE
162 VTND=VTN-CVTND
163 VTD=VTKD+VTND
164 PCTD=VTD*100./VSPL
165 RATD=RDN+RDKT
C
164 CALCULATE MUCSSE FORMATION
165 VISR=EXP(3.2*FW/(1.-CM1*FA))
166 CF=CM2*(WSMS+1)**2*(1.-FW/CM3)*CTIM
167 FW=FW*CF
168 FCW=100.*FW
169 VISEM=VISEM*VISR
C
169 CALCULATE SPREADING (S)
170 CATNS=CS1*(ATN**0.33)*EXP(-CS3*TTN/TTK)*CTIM
171 CVTNS=CATNS*TTN
172 CVTKS=-DVTNS
173 CATKS = CS2*(100/VISEM)*(ATK**0.33)*(TTK-TTN)**1.33*CTIM-CVTNS/TTK
C
172 CALCULATE NEW VOLUMES, AREA, ETC.
173 ATN=ATN
174 ATK=ATK
175 ATCC=ATC
176 VTK=VTK+CVTKE+CVTKD+CVTKS
177 VTN=VTN+DVTNE+CVTND+CVTNS
178 ATN=VTN/TTN
179 ATK=ATK+CATKS
180 TTK=VTK/ATK
C
181 VTC=VTN+VTK
182 ATC=ATN+ATK
183 CATC=ATC-ATCC
184 RATN=(ATN-ATNC)/CTIM
185 RATK=(ATK-ATKC)/CTIM
186 RATST=(ATJ-ATSC)/CTIM
187 RIT=NIT+1
C
188 CALCULATE NEW COMPOSITIONS OF SLICKS
189 FTK=FMAX
190 FTK=FTK+DFTK
191 FT=(FTK+VTK+FTN+VTN)/(VTK+VTN)
192 FTK=FTN-DVINS*(FTN-FTK)/VTN
193 TTK=FTK/(1.0-FW)
C
193 CALCULATE NEW OIL PROPERTIES
194 SOL=SOL*EXP(-SOLK*FTK)
195 CEN = CEN*(1. + CENK*FTK)
196 VISEM=VISEM*EXP(VISK*FTK)
C
196 CALCULATE NEW OIL INPUT (IF ANY) AND SPILL POSITION AND SHAPE
197 ZDR=WSMS*FCR*CTIM
198 IF (VSPL-VOLTS*0.01) 520,521,521
199 SPILL HAS STOPPED
200 521 CVOL=0.0
201 ZDC=ZDD+ZDR
202 CO TO 560
203 SPILL CONTINUES
204 520 CONTINUE
205 ZDL=ZDL+ZDR
206 CONTINUE
207 ZH=0.5*(ZCL+(ZCL+ZEL*16.0*ATC/3.1416)**0.5)
208 ZL=ATO*0.3/(3.1416*ZL)
209 ZLE=ZDL+ZL/2.*200
210 ZTE=ZLE-ZL
C
210 PRINT OUT STATE OF OIL SPILL
C
211 IF (LOOP-NLP) 531,530,530
212 530 CONTINUE
213 WRITE(6,511) VSPL
214 511 FORMAT('1',VOLUME OF SPILL (CUBIC METRES),4X,F9.2)
215 512 CONTINUE
216 WRITE(6,520) NIT
217 520 FORMAT('1',ITERATION NUMBER,10X,I11)
218 WRITE(6,521) TIM,TIMH,TIMM,TIMD
219 521 FORMAT('1',TIM,17X,F9.2,2X,'SECONDS',2X,F9.2,2X,'MINUTES',2X,F9.2,2X,'HOURS',2X,F9.2,2X,'DAYS',/)
220 WRITE(6,532)
221 532 FORMAT('1',30X,'THIN SLICK',10X,'THICK SLICK',10X,'TOTAL',10X,'PERCENT',/)
222 WRITE(6,533) ATN,ATK,ATC
223 533 FORMAT('1',AREA (SQUARE METRES),15X,F15.2,2(10X,F15.2))
224 WRITE(6,534) VTN,VTK,VTC
225 534 FORMAT('1',VOLUME (CUBIC METRES),24X,F8.5,17X,F12.2,13X,F12.2)
226 WRITE(6,535) TTN,TTK
227 535 FORMAT('1',THICKNESS (METRES),27X,F5.6,16X,F9.6)
228 WRITE(6,536) VTN,VTK,VTC,PCTC
229 536 FORMAT('1',INCLUT DISPERSED (CUBIC METRES),12X,F10.5,2(15X,F10.5),5X,F8.2)

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227 WRITE(6,620)FTK,FTK,FT
228 620 FORMAT(' ',FRACTION EVAPORATED',25X,F10.6,15X,F10.6,15X,F12.8)
229 WRITE(6,535) VTAL,VTAL,VTAL,PCTG
230 535 FORMAT(' ',AXCLNT EVAPORATED',27X,F10.6,15X,F10.6,15X,F10.6,4X,F3
231 2,2//)
232 WRITE(6,615)
233 615 FORMAT(' ',PROCCSS RATES PER SECOND//)
234 WRITE(6,616) DVCL
235 616 FORMAT(' ',OIL ADDITION',57X,F12.8)
236 617 FORMAT(' ',FATNG,RATK,RATE
237 617 FORMAT(' ',EVAPORATION',33X,F12.8,13X,F12.8,13X,F12.8)
238 WRITE(6,618) QCAT,70KT,RATG
239 618 FORMAT(' ',DISPERSION',34X,F12.8,2(13X,F12.8))
240 WRITE(6,619) RATON,RATSK,RATST
241 619 FORMAT(' ',SPREADING',33X,F10.4,2(15X,F10.4)//)
242 WRITE(6,354)
243 354 FORMAT(' ',EVAPORATION DATA')
244 WRITE(6,355) VRAT
245 355 FORMAT(' ',EVAPORATION AIR-OIL VOLUME RATIO',18X,F12.3)
246 WRITE(6,356) STN
247 356 FORMAT(' ',OIL-WATER INTERFACIAL TENSION',24X,F5.2)
248 WRITE(6,437) DEN,DENC
249 437 FORMAT(' ',THICK SLICK OIL DENSITY',20X,F10.3,6X,'FRESH WAS',F10.
250 50)
251 WRITE(6,488) SOL,ECLC
252 488 FORMAT(' ',THICK SLICK OIL SOLUBILITY',21X,F10.4,6X,'FRESH WAS',F
253 610.4)
254 WRITE(6,489) VIS,VISC,VISEW
255 489 FORMAT(' ',THICK SLICK OIL PARENT VISCOSITY',15X,F10.4,6X,'FRESH
256 490 WAS',F10.4,5X,'EMULSION VISCOSITY IS',F10.4)
257 WRITE(6,625) PCW,VISR
258 625 FORMAT(' ',WATER CONTENT OF THICK SLICK (VOL PERCENT)',10X,F10.4,
259 510X,'VISCOSITY RATIO',10X,F10.4)
260 WRITE(6,630) TIKEN
261 630 FORMAT(' ',THICKNESS OF THICK EMULSION SLICK',18X,F12.5//)
262 WRITE(6,640)
263 640 FORMAT(' ',SPILL LOCATION AND SHAPE//)
264 WRITE(6,645) ZL,ZW
265 645 FORMAT(' ',LENGTH OF SPILL DOWNWIND',12X,F12.0,2X,'M',5X,'WIDTH',
266 47X,F12.0,2X,'M')
267 WRITE(6,650) LLE,LTE
268 650 FORMAT(' ',DISTANCE DOWNWIND',15X,F12.0,2X,'M',5X,'LEADING EDGE',
269 F12.0,2X,'M',5X,'TRAILING EDGE//)
269 C
270 LOCP=-1
271 531 CONTINUE
272 LCCP=LCCP+1
273 VTK=VTK+DVCL*DTIM
274 VSPL=VSPL+DVCL*DTIM
275 TTK=VTK/ATK
276 FTK=FTK+DVCL*DTIM=FTK/VTK
277 510 CONTINUE
278 RETURN
279 END

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SCATA

TOTAL VOLUME TO BE SPILLED= 100.00 CUBIC METRES

LOCATION OF SPILL (S)
SPILL VOLUME INCREMENTS (M3)
INITIAL SPILL THICKNESS (M)

100.0 CR 0.028 M
100.0 CR SLICK
0.020000 THICK

0.000000 THIN SLICK 8.000000 AREA FACTOR

ENVIRONMENTAL CONDITIONS

TEMPERATURE (DEGREES C) 2.0 CR 35.6 (DEGREES F)
WIND SPEED (MPH) 20.0 CR 3.6 M/S OR 10.8 KNOTS
WAVE FACTOR 0.035

OIL PROPERTIES

DENSITY (KG/M3) 825.627100
VISCOSITY (CPAS) 7.691211
SOLUBILITY (G/M3) 3.000000
VAPOR PRESSURES ARE NOT CALCULATED INDEPENDENTLY

INITIAL VALUE WEATHERING CONSTANT VALUE AT 10 PERCENT EVAPORATION INITIAL VALUE AT 25 C

0.00000000 0.160000 0.00000000 0.00000000
0.00000000 1.600000 0.00000000 0.00000000
1.00000000 12.000000 0.00000000 0.00000000

PROCESS CONSTANTS

EVAPORATION 0.00000000
DISPERSION 0.00000000
EMULSIFICATION 0.00000000
SPLASHING 1.00000000

1.00000000
0.25000000
5.00000000

VOLUME OF SPILL (CUBIC METRES) 100.00
RELEASE NUMBER 1
100.00 SECONDS 1
1.67 MINUTES
0.03 HOURS
0.00 DAYS

THIN SLICK THICK SLICK TOTAL PERCENT

32245.12 22349.02 54594.15
0.1675 98.79 99.95
0.000000 0.004465 0.004465
0.000000 0.000000 0.000000
0.000000 0.000000 0.000000
0.000000 0.000000 0.000000

PROCESS RATES PER SECOND

WAVE ADVECTION 0.00000000
EVAPORATION 0.00000000
DISPERSION 0.00000000
SPLASHING 1.00000000

0.00000000
0.00000000
0.00000000
1.00000000

EVAPORATION DATA
WAVE ADVECTION AIR-OIL VOLUME RATIO 34.662
WAVE ADVECTION INTERFACIAL TENSION 835.2600 FRESH WAS 815.0000
THIN SLICK OIL DENSITY 2.5587 FRESH WAS 2.5587
THICK SLICK OIL DENSITY 7.6917 FRESH WAS 7.6917
WAVE ADVECTION VISCOSITY 0.00000000
WAVE ADVECTION VISCOSITY (VOL PERCENT) 0.00000000
WAVE ADVECTION VISCOSITY RATIO 0.00000000

SPILL LOCATION AND SHAPE

LENGTH OF SPILL DOWNWIND 250.0 M
DISTANCE DOWNWIND 150.0 M
LEADING EDGE 266.0 M
TRAILING EDGE 110.0 M

[illegible]

SPILL LOCATION AND SHAPE

LEA, TH CF SPILL DOWNING
DISTANCE DOWNING

	P	M	WIDTH LEADING EDGE	170A. 762J.	M	M
170B:						
9331:						

TRAILING EDGE

A-18

[illegible]

EMULSION DATA			
CAL-AIR INTERFACIAL TENSION	26.00		
WATER IN OIL VOLUME RATIO	900712.000		
WATER IN OIL VOLUME PERCENT	81.1	FRESH WAS	0.5.
THICK SLICK OIL DENSITY	0.3659	FRESH WAS	3.0000
THICK SLICK OIL SOLUBILITY	10.4468	FRESH WAS	7.6912
THICK SLICK OIL PARENT VISCOSITY			
WATER IN OIL VOLUME RATIO	21.9998	VISCOSITY RATIO	2.1091
WATER IN OIL VOLUME PERCENT	0.00039	EMULSION VISCOSITY IS	22.0267
THICK SLICK OIL PARENT VISCOSITY			
WATER IN OIL VOLUME RATIO			
WATER IN OIL VOLUME PERCENT			

SPILL LOCATION AND SHAPE			
LENGTH OF SPILL DOWNWIND	258.0	M	WIDTH
ESTIMABLE DOWNWIND	153.44	M	LEADING EDGE
			TRAILING EDGE
	2257.0	M	
	1200.00	M	

[illegible]

EXCESS RATES PER SECOND	
OIL ADDITION	
EVAPORATION	C.0000000
DISPERSTION	0.0000000
REPLACING	C.0001280
	0.0001543
	52.7720
	-2.6161
	C.00011826
	C.00051280
	51.1500
EMULSION DATA	
VAPORATION AIR-OIL VOLUME RATIO	1201852.000
WATER-INTERFACIAL TENSION	26.00
THICK SLICK DENSITY	PEA.
THICK SLICK VISCOSITY	0.2498 FRESH WAS
THICK SLICK CIL PALM	107.358 FRESH WAS
WATER CONTENT OF THICK SLICK (WEL	24.9728 PALM WAS VISCOSITY RATIO
PERCENT)	C.50032
THICKNESS OF THICK SLICK (SLICK	22.6862
	2.1091

REFILL LOCATION AND SHAPE
 8801P EF SPILL DEMAND
 1816P EF SPILL DEMAND

3452. P	WIDTH	2469. M	
1816. P	LEADING LOGE	18700. M	TRAILING EGGE

CODE SPACE 00JFCT CODE= 12400 JYLC ARRAY AREA= 0 BYTES, TOTAL AREA AVAILABLE= 73672 BYTES

NUMBER OF ERRORS=	0. NUMBER OF WARNINGS=	1
NUMBER OF ERRORS=	0. NUMBER OF WARNINGS=	1

REVIEW TIME= 0.17 SEC. EXECUTION TIME= 0.70 SEC. 13-12-22 MONDAY 9 AUG 82

DATA FILE'S NAME: S3002700 RUN 12 OF 200 FOR WAFIN STIVER (LUL3)

WAFIN - JAN 1976 VILS

```

*****
* BATFIV VERI LEVS.          WARREN STIVER          MONITOR VERSION 3E *
* MONDAY AUGUST 9, 1982.          1:18 PM *
*****

```

080100 * WARREN STIVER *

CIL SPILL MODEL

NO. 4 FUEL OIL

SET PARAMETER VALUES

SET COMPUTING CONDITIONS

```

TIME INCREMENT IN SECONDS - DTIM
DTIM=100.
TOTAL TIME COMPUTED IN HOURS - TCCMP
TCCMP = 25.0
NITT=TCCMP*3600/DTIM
PRINT OUT FREQUENCY IN HOURS
POFH = 4.0
NLP=POFH*3600/DTIM
NIT=0.0
LOCP=NLP

```

SET SPILL CONDITIONS

```

TOTAL VOLUME SPILLED - VOLTS (M3)
VOLTS=100
DURATION OF SPILL IN SECONDS (MIN IS ONE INCREMENT) - TIMSP
TIMSP=100.0
TIMHP=TIMSP/3600.
TIM=0.0
DVCL=VOLTS/TIMSP
V=OVCL*DTIM
INITIAL THICK SLICK THICKNESS - TTK (M)
TTK=0.02
SHEEN THICKNESS - TTN (M)
TTN=0.000005
ZDL=0.0
ZDD=0.0
VRAT=0.0

```

SET ENVIRONMENTAL CONDITIONS

```

TEMPERATURE - TC (DEGREES C)
TC = 2.
TK=TC+273.
TF=32.0+1.8*TC
WINDSPEED - WSKM (KM/HR)
WSKM=20
WSMS=WSKM/1.6
BSKN=WSMS*1.942
CRIST FACTOR - FOR
FOR=0.035
VDR=FOR*WSMS
THETA = 0.

```

SET OIL PROPERTIES

```

POLAR VOLUME - VVOL (V3/VCL)
VOLAR VOLUME - VVOL (V3/VCL)
MAX FRACTION EVAPORATED - FMAX
ARP = 0.12 - 10.5 * (1.0/295. - 1.0/TK)
BAP = 50.1 - ALG(1.0 - 0.0008*(TK - 295.))
FMAX = 0.2
PTN=0.0
PTK=0.0
E=0.000003
CIL WATER INTERFACIAL TENSION - ST (DYNES/CM)
ST = 30.0
STK=ST
STN=ST
CIL DENSITY - DENJ (KG/M3), WEATHERING CONSTANT - DENK
DEN25 = 900.
CENT = 0.0002
DENC = DEN25 * (1 - DENT*(TC-25))
DENK = 0.12
CIL VISCOSITY - VISO (CPUISE), WEATHERING CONSTANT - VISK
VIS25 = 21.0
VIST = 700.
VISK = 5.0
VISC = VIS25 * EXP(VIST*(1.0/TK - 1.0/298.))
CIL SOLUBILITY - SOLC (G/M3), WEATHERING CONSTANT - SOLK
SOLC = 6.0
SOLK = 12.0
DENS = DENC * (1. + DENT * 0.1)
VISK = VISC * EXP(VIST * 0.1)
SOLK = SOLC * EXP(-SOLK * 0.1)

```

EVAPORATION CONSTANTS

```

CE1=0.00087*(WSKM**0.78)
CE2 = 518.
CE3 = 239.
VTR=0.0
VTN=0.0
VTE=0.0

```

DISPERSION CONSTANTS

```

CD1=0.0002
CD2=2.0
CD3=1.0
VTKD=0.0
VTND=0.0
VTD=0.0

```

EMULSION CONSTANTS

```

CM1=0.65
CM2 = 2.0E-06
CM3 = 0.7
PB=0.0
CP=0.0

```

SPREADING CONSTANTS

```

CS1=1.0
CS2=130.
CS3=5.0
CS4=5.0

```

```

C
C VOLTS IS TOTAL VOLUME SPILLED (CUBIC METRES)
C VSPL IS VOLUME SPILLED TO GIVEN TIME (CUBIC METRES)
C TIM=TIME, TINC, TIME ARE TIME (SECONDS, MINUTES, HOURS, DAYS)
C DTIM IS TIME INCREMENT (SECONDS)
C TIMSP IS SPILL DURATION (SECONDS) (MUST EXCEED TIM)
C DVOL IS SPILL VOLUME INCREMENT
C FMAX IS MAXIMUM FRACTION OF THE OIL WHICH CAN EVAPORATE
C WSKH, WSKM AND WSKN ARE WIND SPEEDS IN KM/H, 1/5 AND KNOTS
C FOR IS WIND DRIFT FACTOR
C TTN, TTK, TTD ARE THIN, THICK AND AVERAGE SPILL THICKNESSES
C ATN, ATK, ATC ARE THIN, THICK, AND TOTAL SPILL AREAS
C (SQUARE METRES)
C VTN, VTK, VTC ARE THIN, THICK AND TOTAL SPILL VOLUMES
C (CUBIC METRES)
C FTK AND FT ARE THIN, THICK AND TOTAL FRACTIONS EVAPORATED
C ST, STN AND STK ARE INITIAL, AND THIN AND THICK SLICK INTERFACIAL
C TENSIONS
C DENC, VISC AND SOLU ARE INITIAL DENSITY, VISCOSITY, AND SOLUBILITY
C OF THE OIL
C DENT, VIST, VORT ARE CONSTANTS RELATING DENSITY, VISCOSITY AND
C VAPOR PRESSURE TO TEMPERATURE
C DEN25, VISC25, VPR25 ARE FRESH OIL DENSITY, VISCOSITY AND
C VAPOR PRESSURE AT 25 DEGREES C
C DENX, VISCX, SOLX, VPRX ARE VALUES OF DENSITY, VISCOSITY AND
C VAPOR PRESSURE AT 10% WEATHERING
C INITIAL RAT INDICATES RATES OF PROCESSES
C ZL, ZW ARE LENGTH AND WIDTH OF SLICK
C ZOL IS DRIFT LENGTH OF THE SPILL SOURCE POINT
C ZOD IS DRIFT LENGTH FROM LAST SPILL POINT
C TEXP IS EXPOSURE TIME (SECONDS)
C
C INITIAL D MEANS DELTA OR DIFFERENCE
C FINAL E INDICATES EVAPORATION
C FINAL D INDICATES DISPERSION
C FINAL W INDICATES EMULSION
C FINAL S INDICATES SPREADING
C FINAL M INDICATES DRIFT
C
C SHUT OFF FACTORS
71 SOFFD=1.0
72 SOFFO=1.0
73 SOFFM=1.0
74 SOFFS=1.0
75 SOFFW=1.0
C
C SHUT OFF PROCESSES
76 FMAX=FMAX*SOFFD
77 CE1=SOFFO*CE1
78 CD1=SOFFO*CD1
79 CM2=SOFFM*CM2
80 CS1=CS1*SOFFS
81 CS2=CS2*SOFFS
82 FOR=FOR*SOFFW
C
C INITIAL CONDITIONS
C
C CALCULATION OF INITIAL DISPOSITION OF OILSLICK
83 VSPL=VI
84 ATK=VI/(TTN+CS4*TTN)
C
C
85 ATN=ATK*CS4
86 ATC=ATK*ATN
87 VTK=ATK*TTN
88 VTN=ATN*TTN
C
C CALCULATE INITIAL OIL PROPERTIES
C
C DENSITY
89 DEN = DENC*(1. + DENK*FTK)
C
C VISCOSITY
90 VIS = VISC * EXP(VISK*FTK)
91 VISCN=VIS
C
C SOLUBILITY
92 SOL=SOL0*EXP(-SOLK*FTK)
93 WRITE(6,305) VCL72
94 FORMAT('11', 'TOTAL VOLUME TO BE SPILLED=', F9.2, 2X, 'CUBIC METRES'//
1//)
95 WRITE(6,712) TIMSP, TIMHP
96 712 FORMAT('11', 'DURATION OF SPILL (S)', 12X, F9.1, 5X, 'OR', F11.3, 2X, 'H')
97 WRITE(6,713) VI
98 713 FORMAT('11', 'SPILL VOLUME INCREMENTS (M3)', 5X, F9.1)
99 WRITE(6,714) TTN, TTK, TTD
100 714 FORMAT('11', 'INITIAL SPILL THICKNESSES (M)', 5X, F11.6, 2X, 'T-ICK
'SLICK', 5X, F11.6, 2X, 'THIN SLICK', 5X, F11.6, 2X, 'AREA FACTOR'//)
101 WRITE(6,715)
102 715 FORMAT('11', 'ENVIRONMENTAL CONDITIONS'//)
103 WRITE(6,350) TC, TF
104 350 FORMAT('11', 'TEMPERATURE (DEGREES C)', 10X, F9.1, 5X, 'OR', F9.1, 2X,
'=', F10.1, 'DEGREES F'//)
105 WRITE(6,351) WSKH, WSKM, WSKN
106 351 FORMAT('11', 'WIND SPEED (KM/H)', 16X, F9.1, 5X, 'OR', F9.1, 2X, 'M/S', 5X,
'OR', F9.1, 1X, 'KNOTS'//)
107 WRITE(6,710) FOR
108 710 FORMAT('11', 'DRIFT FACTOR', 26X, F6.3//)
109 WRITE(6,720)
110 720 FORMAT('11', 'OIL PROPERTIES'//)
111 WRITE(6,731)
112 731 FORMAT('11', '32X, INITIAL VALUE', 12X, 'WEATHERING CONSTANT', 6X,
'VALUE AT 10 PERCENT', 6X, 'INITIAL VALUE', 78X, 'EVAPORATION', 12X,
'AT 25 C'//)
113 WRITE(6,722) DENC, DENK, DENX, DEN25
114 722 FORMAT('11', 'DENSITY (KG/V3)', 16X, F15.6, 3(10X, F15.6))
115 WRITE(6,723) VISC, VISK, VISCX, VISC25
116 723 FORMAT('11', 'VISCOSITY (MPAS)', 14X, F15.6, 3(10X, F15.6))
117 WRITE(6,724) SOLU, SOLK, SOLX
118 724 FORMAT('11', 'SOLUBILITY (G/P3)', 12X, F15.6, 2(10X, F15.6))
119 WRITE(6,704)
120 704 FORMAT('11', 'VAPOR PRESSURES ARE NOT CALCULATED INDEPENDENTLY'//)
121 WRITE(6,705)
122 705 FORMAT('11', 'PROCESS CONSTANTS'//)
123 WRITE(6,726) CE1
124 726 FORMAT('11', 'EVAPORATION', 21X, F15.8)
125 WRITE(6,727) CD1, CD2, CD3
126 727 FORMAT('11', 'DISPERSION', 22X, F15.8, 2(10X, F15.8))
127 WRITE(6,728) CM1, CM2, CM3
128 728 FORMAT('11', 'EMULSIFICATION', 18X, F15.8, 2(10X, F15.8))
129 WRITE(6,729) CS1, CS2, CS3
130 729 FORMAT('11', 'SPREADING', 23X, F15.8, 2(10X, F15.8))
C
131 CC 310 L=1, N=11
132 TIM=TIM+DTIM

```

```

133 TIMM=TIM/60.
134 TIMH=TIMM/60.
135 TIMD=TIMM/24.
C
136 CALCULATE EVAPORATION (E)
137 THETA = THETA + (C1*ATK*CTIM)/(1-PTK)/VTK
138 PTK = ALG((EXP((B2-AR*CE3)*THETA + AR*CE3) + 1.)/(AR*CE3)
139 CVTK = -(PTK-PTK)* VTK/(1-PTK)
140 DPTK = PTK - PTK
141 VRATE = THETA
142 DVTK = - VTK*(PMAX - PTN)/(1-C-PTN)*EXP(-CTIM/500.)
143 VTK=VTK-CVTK
144 VTNE=VTNE-CVTNE
145 VTSE=VTSE-VTSE
146 PCTE=VTE*(C0.0/VSPR)
147 RATE=-DVTK/DTIM
148 RATE=RATE+RATNE
C
149 DISPERSION (D)
150 IF (VISEM.GT.1000.) THEN DO
151 RDK=0.0
152 ELSE DO
153 RDK=CD1+TTK*(WSMS/10.0)**2.0*EXP(-TTK*(CD2*STK/20.0+CD3*VISEM/
154 = 100.0)/0.001)
155 END IF
156 RDN = CD1+TTN*(WSMS/10.0)**2.0*EXP(-TTN*(CD2*STK/20.0)/0.001)
157 RDNT=RDNT+ATN
158 RDKT=RDK+ATK
159 CVTKD=-RDKT*DTIM
160 CVTND=-RDNT*DTIM
161 VTKD=VTK-CVTKD
162 VTND=VTN-CVTND
163 VTD=VTKD+VTND
164 PCTD=VTD*(C0.0/VSPR)
165 RATE=RDNT+RDKT
C
166 CALCULATE MUSSE FORMATION
167 VISEM=EXP(2.5*F*W/(1-CW*F))
168 CF=CM2*(WSMS+1)**2*(1-FW/CM3)*DTIM
169 F=F+CF
170 PC=100.*F
171 VISEM=VISEM*VISEM
C
172 CALCULATE SPREADING (S)
173 DATS=CS1*(ATN*0.33)*EXP(-CS3*TTN/TTK)*DTIM
174 DVTNS=DATN*TTN
175 CVTKS=-DVTNS
176 DATKS = CS2*(100/VISEM)*(ATK*0.23)*(TTK-TTN)*1.33*DTIM-DVTNS/TTK
C
177 CALCULATE NEW VOLUMES, AREA, ETC.
178 ATN=ATN
179 ATK=ATK
180 ATCC=ATC
181 VTK=VTK+CVTK+CVTKD+CVTKS
182 VTN=VTN+CVTN+CVTND+CVTNS
183 ATN=VTK/TTN
184 ATK=ATK+DATKS
185 TTK=VTK/ATN
C
186 VTC=VTN+VTK
187 ATC=ATN+ATK
188 DATC=ATC-ATCC
189 RATS=(ATN-ATC)/DTIM
190 RATS=(ATK-ATC)/DTIM
191 RATZ=(ATN-ATJC)/DTIM
192 NITANIT+1
C
193 CALCULATE NEW COMPOSITIONS OF SLICKS
194 PTN=PMAX
195 PTK=PTK+DPTK
196 PT=(PTN+VTK+PTN+VTN)/(VTK+VTN)
197 PTN=PTN-DVTNS*(PTN-PTK)/VTN
198 TTKEN=TTK/(1.0-PTN)
C
199 CALCULATE NEW CIL PROPERTIES
200 SOLCALC=PI*(ZCL*PTK)
201 CEN = CEN*(1.0 + DUNK*PTK)
202 VISEM=VISEM*EXP(VISEM*PTK)
C
203 CALCULATE NEW CIL INPUT (IF ANY) AND SPILL POSITION AND SHAPE
204 ZDR=ZVS+PCR*DTIM
205 IF (VSPR-VJL*0.001) 520,521,521
206 SPILL HAS STOPPED
207 521 EVOL=0.0
208 ZDC=ZDC+ZDR
209 GC TO 560
210 SPILL CONTINUES
211 520 CONTINUE
212 ZDL=ZDL+ZDR
213 560 CONTINUE
214 ZL=0.5*(-ZCL+(ZCL+ZCL+16.0*ATC/3.1416)**0.5)
215 ZL=ATD*4.0/(3.1416*ZL)
216 ZLE=ZDL+ZL/2.0*ZCO
217 ZTE=ZLE-ZL
C
218 PRINT OUT STATE OF CIL SPILL
219 C
220 IF (LOOP-NLP) 531,532,530
221 CONTINUE
222 WRITE(6,511) VSPR
223 511 FORMAT('1','VOLUME OF SPILL (CUBIC METRES)',4X,F9.2)
224 CONTINUE
225 535 WRITE(6,535) NIT
226 580 FORMAT('1','ITERATION NUMBER',14X,111)
227 WRITE(6,581) TIM,TIMM,TIMH,TIMD
228 581 FORMAT('1','TIME',17X,F9.2,2X,'SECONDS',2X,F9.2,2X,'MINUTES',2X,F9
229 1.2,2X,'HOURS',2X,F9.2,2X,'DAYS')
230 WRITE(6,582)
231 505 FORMAT('1','THIN SLICK',16X,'THICK SLICK',16X,'TOTAL',10X,'PER
232 CENT')
233 WRITE(6,507) ATN,ATK,ATC
234 507 FORMAT('1','AREA (SQUARE METRES)',12X,F15.2,2(10X,F15.2))
235 WRITE(6,508) VTN,VTK,VTD
236 508 FORMAT('1','VOLUME (CUBIC METRES)',24X,F9.5,10X,F12.2,13X,F12.2)
237 WRITE(6,509) TTK,TTN,TTK
238 509 FORMAT('1','THICKNESS (METRES)',17X,F9.6,16X,F9.6)
239 WRITE(6,611) VTD,VTKD,VTD,PCTD
240 611 FORMAT('1','AMOUNT DISPERSED (CUBIC METRES)',12X,F10.5,2(15X,F10.
241 5),5X,F9.2)

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227 WRITE(6,62C)FTK,FTK,FT
228 620 FORMAT(' ', 'FRACTION EVAPORATED', 29X, F10.6, 15X, F10.6, 15X, F12.8)
229 WRITE(6,535) VTNC, VTKC, VTE, PCTC
230 585 FORMAT(' ', 'AMOUNT EVAPORATED', 27X, F10.6, 15X, F10.6, 15X, F10.6, 4X, F8
231 2.2//)
232 WRITE(6,615)
233 615 FORMAT(' ', 'PROCESS RATES PER SECOND//')
234 WRITE(6,616) OVCL
235 616 FORMAT(' ', 'OIL ADDITION', 57X, F12.8)
236 WRITE(6,617) RATING, RATE, RATE
237 617 FORMAT(' ', 'EVAPORATION', 33X, F12.8, 13X, F12.8, 13X, F12.8)
238 WRITE(6,618) RCNT, RCNT, RATE
239 618 FORMAT(' ', 'DISPERSION', 34X, F12.8, 2(13X, F12.8))
240 WRITE(6,619) RATS, RATS, RATE
241 619 FORMAT(' ', 'SPREADING', 33X, F10.4, 2(15X, F10.4)//)
242 WRITE(6,354)
243 354 FORMAT(' ', 'EVAPORATION DATA')
244 WRITE(6,355) VRAT
245 355 FORMAT(' ', 'EVAPORATION AIR-OIL VOLUME RATIO', 18X, F12.3)
246 WRITE(6,356) JTA
247 356 FORMAT(' ', 'OIL-WATER INTERFACIAL TENSION', 24X, F5.2)
248 WRITE(6,487) CEN, DENC
249 487 FORMAT(' ', 'THICK SLICK OIL DENSITY', 20X, F10.3, 6X, 'FRESH WAS', F10.
250 50)
251 WRITE(6,488) SCL, SCLC
252 488 FORMAT(' ', 'THICK SLICK OIL SOLUBILITY', 21X, F10.4, 6X, 'FRESH WAS', F
253 610.4)
254 WRITE(6,486) VIS, VISC, VISEW
255 486 FORMAT(' ', 'THICK SLICK OIL PARENT VISCOSITY', 15X, F10.4, 6X, 'FRESH
256 WAS', F10.4, 5X, 'EMULSION VISCOSITY (S', F10.4)
257 WRITE(6,625) PCN, VISA
258 625 FORMAT(' ', 'WATER CONTENT OF THICK SLICK (VOL PERCENT)', 10X, F10.4,
259 510X, 'VISCOSITY RATIO', 10X, F10.4)
260 WRITE(6,630) TTKEN
261 630 FORMAT(' ', 'THICKNESS OF THICK EMULSION SLICK', 18X, F12.5//)
262 WRITE(6,640)
263 640 FORMAT('0', 'SPILL LOCATION AND SHAPE//')
264 WRITE(6,645) ZL, ZR
265 645 FORMAT(' ', 'LENGTH OF SPILL JOA MAIN', 12X, F12.3, 2X, 'M', 5X, 'WIDTH',
266 47X, F12.0, 2X, 'M')
267 WRITE(6,650) ZLE, ZTE
268 650 FORMAT(' ', 'DISTANCE DOWNWIND', 15X, F12.0, 2X, 'M', 5X, 'LEADING EDGE',
269 F12.0, 2X, 'M', 5X, 'TRAILING EDGE//')
270 C
271 LUGP=-1
272 531 CONTINUE
273 LUGP=LUGP+1
274 VTK=VTK+OVCL*DTIM
275 VSPL=VSPL+OVCL*CTIM
276 ITK=VTK/ATK
277 FTK=FTK+OVCL*DTIM*FTK/VTK
278 510 CONTINUE
279 RETURN
280 END

```

DATA

TOTAL VOLUME TO BE SPILLED= 100.00 CUBIC METRES

QUANTITY OF SPILL (S) 100.0 CR 0.028 M
 SPILL VOLUME INCREMENTS (M³) 100.0
 INITIAL SPILL THICKNESSES (M) 0.020000 THICK SLICK 0.030000 THIN SLICK 8.000000 AREA FACTOR

ENVIRONMENTAL CONDITIONS

TEMPERATURE (DEGREES C) 2.0 CR 35.6 (DEGREES F) 35.6
 WIND SPEED (M/PH) 20.0 CR 5.6 M/PH OR 10.8 KNOTS
 CHPT FACTOR 0.0035

OIL PROPERTIES

INITIAL VALUE BEATHERING CONSTANT VALUE AT 10 PERCENT EVAPORATION INITIAL VALUE AT 25 C
 DENSITY (KG/M³) 516.555000 0.100000 933.056600 900.000000
 VISCOSITY (CPAS) 164.019300 5.000000 278.454800 23.000000
 SOLUBILITY (G/M³) 6.500000 12.000000 1.987762
 VAPE PRESSURES ARE NOT CALCULATED INDEPENDENTLY

PROCESS CONSTANTS

EVAPORATION 0.00693231 2.00000000 1.00000000
 DISPERSION 0.00000000 5.00000000 0.00000000
 EMULSIFICATION 0.64599900 150.00000000 0.00000000
 SPREADING 1.00000000

VOLUME OF SPILL (CUBIC METRES) 100.00
 DISPERALN NUMBER 100.00 SECONDS 1 1.67 MINUTES 0.03 HOURS 0.00 DAYS

THIN SLICK THICK SLICK TOTAL PERCENT
 AREA (SQUARE METRES) 36617.65 5824.30 42441.52
 VOLUME (CUBIC METRES) 0.12200 0.017131 0.00030
 THICKNESS (M) 0.00000 0.00000 0.00000
 PERCENT EVAPORATED 0.00000 0.00000 0.00000

PROCESS RATES PER SECOND

EMULSIFICATION 0.00000000 0.00000000 0.00000000
 DISPERSION 0.00000000 0.00000000 0.00000000
 SPREADING -1.10000000 -24.6823

EVAPORATION DATA
 EMULSION AID-OIL VOLUME RATIO 34.662
 OIL-WATER INTERFACIAL TENSION 917.30.00 FRESH WAS 917.30.00
 THICK SLICK OIL SOLUBILITY 164.0193 FRESH WAS 164.0193
 THICK SLICK OIL VISCOSITY 0.0575 FRESH WAS 0.0575
 WATER CONTENT OF THICK SLICK (VOL PERCENT) 0.01728

SPILL LOCATION AND SHAPE

LENGTH OF SPILL DOWNWIND 212.0 M WIDTH LEADING EDGE 232.0 M TRAILING EDGE
 DISTANCE DOWNWIND 116.0 M

A-26

VOLUME OF SPILL (CUBIC METRES) 100.00
 72%
 72600.00 SECONDS 1210.00 MINUTES 20.17 HOURS 0.84 DAYS
 THIN SLICK THICK SLICK TOTAL PERCENT

AREA (SQUARE METRES) 4595230.00 14248.67 4609578.00 76.11
 VOLUME (CUBIC METRES) 22.97865 53.13 76.11
 THICKNESS (METRES) 0.00000 0.003729 0.003729
 AMOUNT DISPERSED (CUBIC METRES) 11.94954 0.00000 11.94954
 FRACTION EVAPORATED 0.195522 0.055846 0.10214030
 AMOUNT EVAPORATED 8.782877 5.165316 13.948190

PROCESS RATES PER SECOND
 CIL ALDITILN 0.00000000
 EVAPORATION 0.00000000
 DISPERSION 0.00000000
 SPREADING 0.00000000

EVAPORATION DATA
 CIL-WATER INTERFACIAL TENSION 110758.400
 CIL-WATER AIR-TOIL VOLUME RATIO 30.00
 THICK SLICK OIL DENSITY 926.0000
 THICK SLICK OIL VISCOSITY 3.1697
 WATER CONTENT OF THICK SLICK (VOL PERCENT) 221.2590
 THICKNESS OF THICK EMULSION SLICK 0.01243

SPILL LOCATION AND SHAPE
 LENGTH OF SPILL DOWNWIND 2822. M
 DISTANCE DOWNWIND 15322. M
 WIDTH LEADING EDGE 2433. M
 TRAILING EDGE 15604. M

VOLUME OF SPILL (CUBIC METRES) 100.00
 871
 87100.00 SECONDS 1451.67 MINUTES 24.19 HOURS 1.01 DAYS
 THIN SLICK THICK SLICK TOTAL PERCENT

AREA (SQUARE METRES) 5499246.00 11536.44 5510782.00
 VOLUME (CUBIC METRES) 27.46223 41.10 68.56
 THICKNESS (METRES) 0.000005 0.002562 0.002562
 AMOUNT DISPERSED (CUBIC METRES) 12.11588 0.000000 12.11588
 FRACTION EVAPORATED 0.426830 0.000000 0.426830
 AMOUNT EVAPORATED 5.456127 0.000000 5.456127

PROCESS RATES PER SECOND
 CIL ALDITILN 0.00000000
 EVAPORATION 0.00000000
 DISPERSION 0.00000000
 SPREADING 0.00000000

EVAPORATION DATA
 CIL-WATER INTERFACIAL TENSION 136434.100
 CIL-WATER AIR-TOIL VOLUME RATIO 30.00
 THICK SLICK OIL DENSITY 927.30500
 THICK SLICK OIL VISCOSITY 2.9489
 WATER CONTENT OF THICK SLICK (VOL PERCENT) 228.0165
 THICKNESS OF THICK EMULSION SLICK 0.01187

SPILL LOCATION AND SHAPE
 LENGTH OF SPILL DOWNWIND 2649. M
 DISTANCE DOWNWIND 14251. M
 WIDTH LEADING EDGE 2649. M
 TRAILING EDGE 15610. M

CORE USAGE COLLECT CODE = 12400 BYTES, AREA = 0 BYTES, TOTAL AREA AVAILABLE = 73672 BYTES
 DIAGNOSTIC NUMBER OF ERRORS = 0. NUMBER OF WARNINGS = 1
 COMPLETE TIME = 0.17 SEC, EXECUTION TIME = 0.72 SEC, 13.18.58 MONDAY 9 AUG 82 MATP1V - JAN 1976 VILS
 SP45P1V5 SACT 33002704 HLA 15 OF 200 FOR WARNER SILVER (LUU3)

**DA
FILM**